PROCEEDINGS
THE INSTITUTION OF CIVIL ENGINEERS

PART I
SEPTEMBER 1956

JOINT MEETING *

THE INSTITUTION OF CIVIL ENGINEERS
THE INSTITUTION OF MECHANICAL ENGINEERS
THE INSTITUTION OF ELECTRICAL ENGINEERS

at the Institution of Mechanical Engineers

16 January, 1956

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Paper No. 6157

ADVANCED COURSES FOR ENGINEERS IN INDUSTRY

by

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Part I

by H. D. Morgan

THERE is some misapprehension as to the meaning of the word "education". It is too frequently considered that it should be vocational and no more. Scholarship for its own sake is no longer desired as it once was. Specialization is on the increase and the demand for scientific and technical man-power is so great that the mind-training aspects of education are tending to be forgotten in the race to meet

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the ever-increasing demand for technologists. There is a need for individuals who can think on broad lines, and to supply this it is by no means certain that the technical training favoured today is comparable with the classical education of yesterday.

There is a great need for sensible technical executives as well as experts; that is, individuals with common sense who can shift their thoughts rapidly from one subject to another, can assess the claims of the experts, balance technical elegance against economy, and, above all, deal with problems which are new to them and unrelated to their technical training. The importance in all problems of the common sense viewpoint cannot be overstressed; in any system of education the development of this side of the student's mind should take an important place.

This introduction may seem at first sight a little removed from the subject of this paper but it is because specialization is tending to appear even in universities and schools that the need for a broad treatment of advanced courses is so great. At present technical knowledge accumulates far more rapidly than human wisdom increases; what is more, technologists sometimes seem the least aware of the real object of their work. This is a view that has been expressed before but it is ignored so often in technological education that its repetition may perhaps be pardoned.

It may be asked whether full use would be made of increased opportunities for advanced education. Human inertia is hard to overcome. Some consider that they need learn no more after leaving school or university, while others recognize the desirability of so doing but feel they have not the time available. In either case the fault lies more often with the individual than in the lack of opportunity. Present and possible future facilities only will be considered here, and it will be assumed that the desire to make use of them exists.

Before attempting a detailed survey of the present requirements for advanced courses for civil engineers and of the extent to which these can be met, it would be useful to consider the case of a typical graduate—or trainee with similar qualifications—who is embarking on his career and taking the measure of what he knows and what he can do. He will have acquired a broad idea of the general principles of the several branches of engineering and a more detailed knowledge of the branch which he has adopted—civil engineering in this case. He will have a mathematical grounding, some knowledge of geology, materials, structures, and hydraulics; also of drawing and surveying. However, there is a notable list of subjects about which he will know very little but which occupy much of the practising engineer's time. These include preparation of reports; organization and planning of work; preparation of contract documents; economics of design; quantities and measurements, and legal and labour problems.

In addition, there are associated subjects such as architecture, agriculture, and welfare for which the engineer is seldom directly responsible but which are often involved with his work.

The author personally regrets the alteration made by the Institution of Civil Engineers in the form of their final examination for corporate membership. The professional interview, which is an innovation, has much to commend it but it should constitute an addition and not be in substitution of the former examination in Conditions of Contract, Specifications and Bills of Quantities. The young engineer, not unnaturally, now tends to dismiss these subjects as of minor importance.

Apart from these gaps in his knowledge the graduate finds that in spite of lengthy training he is not yet equipped to prepare designs and contract documents for works without a great deal of supervision. If, however, his education has been successful in teaching him to think clearly, his mind will be in a receptive state and he will be

eager to fill in any gap, not only through practice but also by further personal study. There is thus a need for further education as soon as the young engineer qualifies. Later the more experienced engineer, now possibly approaching middle-age, will find new techniques and methods of design appearing which were not available in his university days. He will also find that he is forgetting subjects in which he has not happened to have had any opportunity of gaining practical experience.

The author has nearly completed thirty years in the profession, almost fourteen of these being as a partner in a firm of consulting engineers. It has been found that men tend to fall into two main groups: those who seem to prefer and do better at administrative work and others who prefer the purely technological work. This tendency is so marked that it has often been found necessary to have two men working on parallel lines at the head of a section dealing with a specific work. It is believed that the reason for this tendency towards segregation is that on the one hand the individual who finds his technical subjects quite easy at the university, becomes wrapped up in them to the extent that he grudges the time to deal with the other aspects of the work, while another, who does not find his technical subjects quite so easy, finds his outlet in planning and organization. The best and most valuable men are undoubtedly those who combine these abilities, but they appear to be rare.

It seems, therefore, that a valuable service could be rendered to the industry and the individual if means could be found for engineers of experience, not only to study new methods and techniques which have come into being since their period of training was completed, but also to enable them to study, if they wish, the aspects of their work which they find difficult to approach and thus, as it were, adjust the balance of their experience.

A list is given below of the subjects in which it is suggested courses of instruction would be valuable. The first main group contains subjects which arise in the administration of engineering work. The second main group concerns technical matters; that is, methods of design and the use of modern techniques.

Group I—Administration

1. Preparation of reports—structure and composition
2. Contract procedure
3. Preparation of estimates and make-up of costs

Group II—Technical

1. Modern concrete technology
   - (*a*) *Preparation of concrete*
     - (i) Mix design
     - (ii) Quality control
   - (*b*) *Concretes for special purposes*
     - (i) "Zero slump" concrete
     - (ii) Resistance to frost and abrasion
   - (*c*) *Ready-mixed concrete*
   - (*d*) *Use of additives*
   - (*e*) *Placing of concrete*
     - (i) Transport by skip
     - (ii) Compressed-air placing
     - (iii) Concrete pump
     - (iv) Placing underwater

(v) Placing in cold weather
(vi) Vibration and revibration
2. Prestressed concrete
3. Welded steel structures
4. Aluminium alloys in structural engineering
5. Soil mechanics

The subjects shown in these groups will be discussed briefly in order to amplify the reasons for their selection.

GROUP I

1. *Preparation of reports—structure and composition*

It is a matter of continuing experience that many young engineers—and some older ones—seem to find difficulty in drawing up a technical report presenting the facts and conclusions in an orderly and logical manner. It would be valuable if something could be done to correct this, and also to encourage a higher standard of English.

2. *Contract procedure*

A young engineer when first starting work knows practically nothing of the subject of contract procedure in general. He comes into contact with problems involving the interpretation of the contract, measurement, day works, variations and the like, and learns how to deal with these matters by experience. It is believed that many would profit from having the opportunity of attending lectures on the general contractual framework within which an engineering contract is carried out. Having grasped this, the engineer will much more quickly absorb and fit into their proper places the many and various facts which will be learned by experience.

3. *Preparation of estimates and make-up of costs*

In making estimates of costs, the first step obviously is to divide up the work into suitable classes and to estimate the quantity of each. Unit prices for each item of work must then be found. The only sound way of doing this is to build up the cost by methods in use by Public Works contractors, large and small; that is to say, by making up the prime cost of a unit of work from the cost of materials and labour, and then making an addition representing the proper allocation of overhead costs and plant costs. Unless they have had experience in the appropriate department of a contractor's organization, many young engineers do not understand these processes. It is believed that facilities for instruction on the general principles would be appreciated.

GROUP II

1. *Modern concrete technology*

(*a*) *Preparation of concrete*

(i) *Mix design.*—A great deal has been written in recent years on the subject of mix design, and this has included the results of valuable research work. It remains a fact, however, that for a specific work, the methods used to arrive at the proper mix must be to some extent empirical and, generally speaking, depend upon the supplies of aggregate and sand which are readily obtainable at or near the site. The material will rarely be ideal and mix design will resolve itself into the study of how to make the best use of the materials which are economically available. This frequently

means the acceptance of some sort of compromise. It is not only necessary for the engineer to understand the significance and effect of the shape of aggregates, the nature and fineness of sand, specific surface of the aggregates and the like; he also requires practice in making test mixes so that the variations to be made in the factors involved can be sensed. In this case it is experience under controlled conditions that is required. Expert concrete technologists have stated that it takes intensive training for about a year to equip a man to do this sort of work unsupervised. It is believed that some opportunity for practical work in this field would be welcome.

(ii) *Quality control.* The requirements for making first-class concrete are now fairly well understood; the difficulty is to get them carried out. It is a commonplace to see a most up-to-date weigh-batching plant installed at site, only to find that its advantages are not being made use of because insufficient notice, or no notice at all, is taken of the moisture content of the aggregates. Here again the principles underlying control of quality are reasonably widely known, but many engineers do not know how to apply them.

(*b*) *Concretes for special purposes*

(i) "*Zero slump*" *concrete.*—Occasionally it is very desirable to be able to strike shuttering very early, so as to obtain the maximum number of uses from each set of shuttering, or in order to give special treatment to the surface of the concrete, as for instance in constructing a wind tunnel. This is a profitable new technique, and one which should be dealt with in any course of Concrete Technology (Stewart 1951).*

(ii) *Resistance to frost and abrasion.* The design of special mixes for resistance to frost and abrasion, for compaction by surface vibrators and for association with the vacuum process, has recently been dealt with (Cement and Concrete Association 1954), and should form part of any advanced course.

(*c*) *Ready-mixed concrete.*—The use of ready-mixed concrete is a fairly recent innovation. The principles involved are not widely known and this information should be made available.

(*d*) *Use of additives.*—The use of additives in concrete is becoming more and more general. Many of these are of considerable value for achieving watertightness, density, plasticity, frost resistance, and so on, but since they are largely of a proprietary nature the general principles underlying their effects are not widely understood. Nevertheless authoritative papers have been written dealing with this subject in principle (Valenta 1948; Leviant 1952; Duriez 1953; Ammann 1954, 1952) and the results of a great deal of research work are available.

Very considerable use is made of these additives on the continent of Europe, and they are likely to be increasingly used in Britain. The practising engineer should be able to inform himself more readily on this subject.

(*e*) *Placing of concrete.*—It is believed that many engineers would be surprised to know the extent to which concrete may undergo segregation after leaving the mixer, owing to the inherent characteristics of the plant used to handle it, although correctly mixed initially. The fact is frequently not detected because samples taken from the concrete as finally placed in position are made into the routine test cubes for control

* An alphabetical list of references is given in the Appendix.

of strength, but are seldom analysed to check the mix. The author recalls a case recently when concrete was brought from the batching and mixing plant to a part of the works by dumper which discharged close to the work; skips were then filled for lowering into the cofferdam—two skips to each dumper load. Segregation took place during the transit of the dumper and the first skip load was invariably quite different in composition from the second. In another case, reinforced concrete piles were made in a yard very close to the mixing plant and the concrete showed a high strength. This was never again equalled when transport had to be effected to more remote parts of the site. Similarly, compressed air placers and concrete pumps have tricks of their own which should be fully understood. The use of this type of equipment is essential in tunnelling work, but unfortunately a mix design to ensure a minimum of shrinkage is often unsuitable for pumping.

The placing of concrete under water is an operation in which special knowledge is essential. Excellent concrete can be so placed, provided the proper precautions be taken, but success very often depends on some point which may appear trivial to the site personnel. It is essential to ensure that successive increments of concrete be made to flow into the work and on no account be allowed to fall, however short the distance. Even with simple equipment like a box with bottom doors, excellent underwater concrete can be achieved. The crane driver is instructed to lower each box at the point where the preceding one was released by the diver. In this way the loaded box is used to press down the last load before being signalled away by the diver and itself discharged.

It is frequently necessary to continue with works throughout cold weather in order to maintain an essential programme. This can be done quite successfully by adopting special methods.

All concrete of high quality requires vibration when placing. It is not generally known, however, that successive revibration at 15-min intervals approximately, will achieve even higher ultimate strength. With ordinary Portland cement, concrete treated in this way still shows an increase in ultimate strength when vibrated up to four hours after placing, with the optimum strength at two and a quarter hours. The use of an agent to retard the initial set will enable the concrete to be revibrated for substantially longer periods. A most interesting use of this phenomenon was made in the case of the Tarrytown Bridge over the Hudson River, when main beams 50 ft long, 12 ft deep, and 8 ft wide were continuously concreted, the poker vibrators being put through each new lift and down into the concrete below. By the time the top lifts were placed, that at the bottom had sufficient strength to relieve the centring of a substantial part of the load. Although this beam was concreted continuously, no subsequent cracking was observed.

The author believes that a complete advanced course could be built up under this heading, and that a very considerable amount of the special knowledge and experience could be assembled in these special techniques, including the use of special skips provided with paddles for remixing, and operated by compressed air.

2. *Prestressed concrete*

The design of works in prestressed concrete does not present much difficulty to an engineer who is already practised in the design of normal reinforced concrete structures. It is necessary, however, for him to understand the special techniques and equipment of prestressing the steel. This is particularly true in post-tensioned work. Quite commonly, the majority of the engineers at site have never seen it done before, although this will less frequently be so in the future. Any facilities which could be

provided for engineers to gain practical knowledge on this subject would be of great value. It is the opportunity for practical work which is so important here. It should not be particularly difficult to arrange for pre-tensioned units which are factory made, but opportunities for seeing and practising post-tensioning operations are likely to be difficult to arrange.

3. *Welded steel structures*

The average engineer learns all the essentials of normal structural steel work when he receives his technical education. This refers to bolted and riveted structures. Today an increasing use is being made of welded structures, the most common being fabricated by shop welding and often assembled by bolting at the site, though some are also welded at the site. There is a lack of knowledge of these techniques in the profession, and opportunities for instruction would be welcome, including a knowledge of shop practice. Such a course should include the treatment of continuous frames and an up-to-date review of the available methods of testing welds. It is most important that professional engineers should know more about these subjects, since there is probably no technique in engineering in which so much depends not only upon the skill but also upon the integrity of the operator. Horrible examples of welding are to be seen on every civil engineering site, usually perpetrated by some member of the "black gang" as a sideline. It should be made quite clear, of course, that these do not form part of any permanent works, but are usually to be seen on the contractor's plant and equipment.

4. *Aluminium alloys in structural engineering*

The use of aluminium alloys for structural work is becoming of increasing importance, and it is not generally realized that a large number of standard special alloys is available. In some cases a use of aluminium is essential: for example, in factories for the manufacture of special electrical equipment, such as flux valves for aircraft. It is believed that the opportunity for instruction in this special subject would be welcome.

5. *Soil mechanics*

All young engineers at the present time are, quite properly, taught the principles of soil mechanics at the university, and this must involve a certain amount of practical work. They appear, however, to suffer from the disadvantage of not having had enough opportunity for field work. It would be of value if this could be corrected, but it is difficult to propose how it should be done. It is not suggested that the consulting engineer or contractor should make his own investigation: it is far more practicable to employ specialist firms, although some large contractors have their own soil mechanics laboratories. The point is that a better knowledge of the actual practical side of sampling and testing would enable most engineers to interpret much more clearly the results and reports which are submitted to them.

Existing facilities

Having discussed the desirability of advanced courses, it now remains to examine the existing facilities and to see how far these meet the requirements. There is a fair number and variety of courses available in London and the other large centres at technical colleges and mainly in the evenings.

Table 1 shows the advanced courses for civil engineers which are available at the

present time, either in London or in other parts of Britain. It has been found that subjects numbers 1–10 inclusive are the more common, numbers 11–15 more rare.

TABLE 1.—ADVANCED COURSES FOR ENGINEERS

1. Foundations and sub-soils
2. Soil mechanics
3. Design of welded structures
4. Modern structural analysis
5. Structural stability
6. Reinforced concrete (advanced)
7. Prestressed concrete
8. Shell concrete roofs
9. Concrete technology
10. Aluminium alloys in structural engineering
11. Specifications and quantities for civil engineering contracts
12. Elements of law relating to civil and mechanical engineering
13. Organization of civil engineering contracts
14. Administration of acts controlling building
15. Accountancy and costing

Although courses are available to a substantial proportion of the profession, there are many in isolated parts who cannot attend them at all, and even more who would have to undertake long and exhausting journeys to do so. For these there remains only the correspondence courses which, although they have obviously given a useful service, can be little better than independent reading with a little direction and some discipline added. By their very nature and regardless of how well they are thought out and administered, they are clearly the least satisfactory form of education.

Evening classes represent a great improvement over correspondence courses, and it would be fitting here to make an acknowledgement to the technical colleges and polytechnics which are almost alone in providing these. In London especially they provide excellent courses on most of the new techniques such as prestressed concrete and soil mechanics, as well as a wide variety of lectures on the more basic subjects which could well be used as detailed refresher courses although they are not necessarily intended as such.

In spite of the admirable work which they do, the technical colleges do not, except in isolated cases, meet the needs on the more general subjects not usually covered at the universities, and they do not give concise refresher courses to suit the executive who has already had a full technical education. Also evening classes have inevitable drawbacks however well they are conducted. In the first place the minds of the students and sometimes perhaps that of the lecturer are already tired by a full day's work; secondly, the courses are usually too extended—often a whole winter for a single set of lectures—with the result that uninterrupted attendance is rarely possible, gaps being caused either by illness or exigencies of the student's employment.

Whole-time studies for periods varying from, say, three days to three weeks could be preferable to evening classes for almost all advanced education, but at present the number of available courses of this type is very small indeed. Inevitably, such courses would interfere with the engineer's normal work, and his employer might well be unable to allow him a week or two of study time in any year in addition to his annual holiday, especially since those best fitted to benefit would probably be those least easy to spare. However, few men are indispensable and, if the practice of

allowing study time were to come about gradually, the employer might feel that the benefits were equivalent to the disadvantages.

With such concise courses, the problem of mental fatigue associated with evening classes would be largely solved and the student would be able to concentrate his mind wholly on the subject during the period of the course. Further, the courses would become available to many of those living in comparatively remote parts who could not attend evening classes.

The universities, which at present do not provide for additional education later than their normal post-graduate courses, seem almost ideally placed to give concise advanced courses, especially those on the more general subjects. These could possibly be given during the vacations, when lecture rooms would be free and when demonstrations could be arranged without interfering with routine laboratory work. Further, rooms and meals would often be available at reasonable rates for those attending. It is believed that many university lecturers would be glad to co-operate, and such courses might also help the residential colleges by giving more regular employment to their other staff throughout the year. Apart from the universities, certain of the government technical departments and trade associations might well provide courses. Such an association has recently sponsored a most valuable symposium on concrete technology.

Recently also the Building Research Station and Road Research Laboratory have been holding "open days". These might be extended to include brief courses of lectures which would perform the additional service of bringing the research staff in such establishments into still closer contact with the industry.

There is no reason why the technical colleges and polytechnics should not also give short full-time courses, but it might be more practicable for them to concentrate on broadening the range of their evening classes to cover a wider variety of subjects. This would be attractive to those unable to spare the time for full-time study and also to those who wish to take, perhaps, two or more courses in a year.

The cost of such courses should be kept as low as practicable. If it were possible to provide a measure of financial assistance, this would certainly encourage full utilization. Certain branches of industry have recently shown considerable generosity in similar circumstances and it would be reasonable to hope for some help from this direction and possibly from the Government which, owing to its several commissions and authorities, must now be interested more than formerly in this subject.

The scope of this Paper has now been covered if not in great detail, at all events in outline. The need to avoid specialization too early in education has been stressed; his is not strictly within the terms of reference of the Paper but it is of importance from the viewpoint of equipping the individual to play as full a part as possible in his profession. It is believed that a real need exists for advanced courses for engineers. Given an intelligent and realistic approach by the educational faculties and employing authorities, some satisfactory solution appears to be quite possible. It is felt that the practising engineer would gain a great deal and in so doing he would be of greater value to his employer, and therefore to himself.

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Part II

by Professor G. F. Mucklow

Post-war conditions have made it clear that Britain, unable to produce food for her huge industrial population and handicapped by declining natural resources, must increasingly depend for her well-being on an expanding level of exports of engineering products of all kinds.

It is equally clear that the effectiveness of these products must be measured, not by mere weight or volume, but in terms of the technical skill and brain-power embodied in each pound of material. In fact, the sole hope of combating growing competition from overseas lies in better craftsmanship, improved methods of production, more advanced design, and greater imagination and initiative in the application of scientific thought and discovery.

The matter thus resolves itself essentially to one of education and training, there being two separate problems involved: The first is that of increasing, at each level, the number of young men entering the engineering industry and of providing suitable facilities for their basic education and training. The second problem, that of maintaining and increasing the technical efficiency and professional ability of those actually engaged in engineering, involves both a short-term and a long-term requirement. The former is to ensure the rapid dissemination throughout industry of the latest knowledge and information regarding new methods and techniques, so that those concerned shall be kept continually abreast of each fresh advance and development. Of no less importance is the long-term necessity of providing for future technical leadership. This demands that throughout industry, young engineers of particular promise should be picked out for special training, so that to their knowledge of the practical aspects of their chosen fields may be added a thorough understanding of the related fundamental scientific concepts and of the possibilities and limitations thereby dictated.

The first of these problems has formed the subject of a profusion of reports and papers. Many and varied suggestions have been made, both as to the best means of meeting the anticipated demand for recruits to the engineering industry and in regard to the methods to be adopted for the training and education of these recruits. So far as quality of product is concerned, however, available evidence tends to show that the systems in use in Britain compare, on the whole, not unfavourably with those in vogue elsewhere. Thus it would seem that the solution to the first problem lies in diverting the interest of a larger proportion of the youth of the nation towards engineering and in expanding the output of university engineering schools and technical colleges. Discussion of the methods whereby this is to be achieved is, however, outside the scope of this Paper.

The second problem—that of providing for continued engineering education and training—has attracted comparatively little attention and, perhaps for this reason, its importance has not received the widespread recognition it deserves. It is indeed

little exaggeration to say that, except in so far as its short-term aspects are concerned, engineering firms in general remain as yet unconvinced of the existence of the problem and still less of its urgency. This outlook, indeed, forms a serious difficulty, since, given the wholehearted interest and support of industry, the solution of the problem would not be far to seek. The simplest and most efficient method is undoubtedly to build on the existing educational system, and to increase the number and range of advanced courses of the types already offered by a number of university engineering schools and technical colleges.

The duration, the subject, and the level at which that subject is treated must obviously depend on the circumstances and, in particular, on whether the objective is of a long-term or of a short-term nature. Thus, if the requirement to be met is a short-term one, the course is likely to be of short duration and narrowly specialized. For instance, when the object is the dissemination of information regarding some specialized technique or method, for the benefit of an individual firm or group of firms, the course may well consist of a series of evening lectures given at the neighbouring technical college. For other, but still short-term requirements, as for example the "refresher" course or the course for specialists, designed to cover some limited aspect or application of their own speciality, a full-time course of a few days, a week, or even longer may be suitable. The arrangement of the course may vary from a few part-time lectures to a carefully organized residential summer school. The range of topics appropriate to such courses is well-nigh inexhaustible and the levels at which those topics are treated may differ widely. In the majority of cases, however, courses of the short-term type will be planned to cater for the more immediate needs of industry and to deal with matters closely related to contemporary problems of design and manufacture. It would seem therefore that, in general, the organization and conduct of such courses is a duty best undertaken by the technical colleges, by virtue of their situation in close contact with industry and of their ability to draw upon engineering firms and similar organizations for assistance in the matter of staff.

It does appear, however, that the shorter the duration of the course, the more specialized must be the subject dealt with and the more superficial the treatment of that subject. On the other hand, the benefits resulting from the short-duration course are quickly felt and, at the same time, no prolonged absence from their normal duties is incurred by those attending. If only for these reasons, also, it is to be expected that courses of this type should appear more attractive to industry and should therefore be less difficult to establish than where the object of the course is of a more long-term nature and its duration correspondingly increased.

Although, particularly for purposes such as the spreading of information regarding contemporary practice, short courses of the kind referred to are not only of the utmost value but are indeed a necessity for the continued health of industry, the need which they serve is of an immediate and short-term character. They are essentially different from, and can in no way replace, the full-scale graduate course, where the object is to cater for the future rather than the present. From the long-term point of view, the imperative need for this type of course cannot reasonably be disputed. To retain supremacy in world markets demands that in each specialized branch of engineering there should be young men of special promise coming forward who are equipped to form the spearhead of future progress. To keep abreast of the rising tide of knowledge, to be able to interpret and to apply each fresh advance and new development as it arises, requires from these men something more than the complete mastery of the accepted methods and techniques in their own fields of endeavour.

They must possess also a deep insight into the theoretical aspects of those fields, coupled with the breadth of vision springing from a thorough familiarity with advanced concepts in other and related spheres of pure and applied science. The acquisition of this fundamental knowledge can result only from full-time study undertaken under suitable guidance and in an atmosphere freed from the distractions of industry.

To locate and collect from widely dispersed sources the information he requires and to study, unaided, completely new subjects, involving unfamiliar notations and treatments, can only represent to the engineer engaged in the routine of his profession an intolerable addition to his normal duties. The solution lies in the provision of carefully planned, full-time, courses of instruction, to which a relatively small number of selected young men may return after having achieved some measure of responsibility in the appropriate industrial sphere. By this means only can such men be provided with the requisite opportunity to study in an organized and intensive manner the advanced concepts and techniques in their own and related fields.

In certain of the larger engineering concerns, the thought has arisen that courses of the nature considered might well be conducted internally by staff members of the organization itself, some of them perhaps appointed for this especial purpose. This suggestion, though offering a possible means of satisfying immediate needs for courses of the short-term type, is wholly unsatisfactory where the intention is to provide balanced facilities for properly directed study in a range of subjects at really advanced level. For such courses fully to achieve their purpose, no half-measures will suffice and both the highest possible standard of teaching and an adequate allowance of time are essential. The detail planning of an appropriately balanced syllabus and the preparation of the required series of lecture courses at the level envisaged is a matter not to be undertaken lightly, and certainly not as a part-time addition to other work. To teach at advanced level requires in the teacher himself the habit and background of study at advanced level. To choose well the syllabus appropriate to a course of the type considered demands a certain detachment of view-point and freedom from the bias of immediate commercial interest. It is one thing for a member of an engineering firm to deliver a single paper or a few lectures on some subject closely related to his daily work; it is quite another to expect him to undertake serious teaching in a range of subjects of a fundamental and theoretical character. From every point of view, this duty is better left to experienced members of the teaching profession, working in the atmosphere of an institution created for the specific purpose.

The type of educational establishment best fitted to undertake the courses in view must depend on the particular circumstances, and no hard-and-fast rule can be laid down. It is recognized that the organization and conduct of graduate-level courses forms an activity which may with advantage be undertaken by certain types of college and institution other than the universities. The task is, however, essentially one for which the universities are pre-eminently well fitted, and it is envisaged that the organization of advanced courses of the long-term type is a duty which will normally be their concern. It is indeed for exactly this purpose that graduate schools in selected branches of engineering science have within recent years been established in association with a number of university departments of engineering.

The situation of these graduate schools within a university, in proximity with established schools of pure and applied science and in an atmosphere permeated with the fertilizing influence of research, is peculiarly appropriate to the function which they are designed to discharge. Courses at the level and of the quality envisaged are

not possible except on the basis that teaching and research must go hand in hand.

The graduate school should therefore operate in close contact with the existing school of research which forms an essential part of any university engineering department of standing and repute. Although the two schools should normally share the same field of interest, the work for which they are designed is, however, essentially different in character.

In the research school, the student is normally engaged on an investigation directed towards the solution of a specific problem. The value of his training lies in the development of the critical or research attitude of mind, in the opportunity to practise the application of theoretical and experimental methods of analysis and synthesis, and in the experience he gains of the basic procedure to be adopted in the approach to a new problem. The attainment of these objectives, involving the development of experimental techniques, the correlation and analysis of observed data, the build-up of theoretical arguments and the extraction of conclusions, can only be realized at the expense of certain sacrifices. The interest of the student is necessarily focused on one particular topic, the subjects of his reading and thought tend to be restricted to a narrow field and little opportunity occurs to pursue to advanced levels any wider range of studies. Though rectified in some degree by contact with colleagues engaged on other projects, these deficiencies are unfavourable to the development of the inspiration and breadth of vision brought by familiarity with topics related only indirectly to those under immediate consideration. Thus, despite its recognized value for particular purposes, the training received by the research student is no substitute for the organized courses of instruction which it is the function of graduate schools of the type under consideration to offer.

Since the expressed aim is to cover a range of subjects related to some chosen field of engineering, rather than a single topic, at a level which must inevitably call for sustained hard work on the part of the student, the courses given in these schools must necessarily be of relatively long duration. The habit of concentrated study is not immediately redeveloped after a break of some years. To establish a common starting level in a group of graduate students would necessitate a period of acclimatization, even assuming each individual to possess a basic education in engineering science of identical standard and scope. Experience shows, in fact, that to achieve fully the purpose of a course of the type considered, where the aim is essentially of a long-term character, a duration of some nine to twelve months is essential. If results of real and lasting value are to be obtained, this fact must be faced. To reduce the above period or to substitute a series of short courses, each dealing piecemeal with a single topic within the chosen field, is to preclude close study of the relations between those topics and to defeat a primary object of the course. The courses themselves should normally comprise formal lectures, tutorial classes, and laboratory work, the latter being designed to illustrate the treatments developed during lectures, to permit experimental confirmation of the results of mathematical analysis and theoretical argument and to afford familiarity with modern techniques of instrumentation. The general orientation should be towards the scientific approach, and the courses, although restricted to the chosen field of engineering science, should be in no way specialized in the narrow sense. Detail matters of engineering design and practice are suitable only to be treated adequately at advanced level by men in day-to-day contact with industry and, as such, should be avoided.

Although it is suggested that the possession of an honours degree in engineering should be a normal prerequisite to admission to these schools, the only true measure

of a candidate's fitness for entry is that he should possess the ability to profit fully from the course. It is thus considered undesirable that acceptance should be denied to non-graduate engineers who hold satisfactory alternative qualifications or, in special cases, to graduates in other sciences having appropriate engineering experience. On the other hand, the possession of several years experience of industrial engineering should be demanded in all cases, without exception. The reason for this requirement is obvious, in view of the type of man for whom these courses are designed to cater. Thus it is not until some years after graduation that such men are likely to have found themselves committed definitely to the advanced problems of design or development in some particular field. Until this stage is reached, however, the need for a further course of advanced study will not normally have become urgent, nor will it have become possible to decide as to the exact range of subjects in which further study should be undertaken.

Although the establishment of graduate schools of the type considered offers to the engineering industry a long-term investment which cannot fail eventually to yield handsome dividends, there remains a formidable difficulty to be overcome. However well-planned the courses and however appropriately chosen their individual fields of interest, the success or failure of the scheme must ultimately depend on the degree of support and co-operation received from industry itself. Thus it is unlikely that a young engineer in industrial employment will be able to return to the university to attend a graduate course without the support and encouragement of his employers. He will in any case be reluctant to do so unless satisfied that his immediate seniority will not be prejudiced and that his ultimate prospects will be enhanced. It is also but natural that a senior engineer should be reluctant to lose a promising junior for some nine to twelve months without clear proof of the solid value and worth of the course it is proposed that he should attend. The establishment of graduate schools is admittedly a new venture and, for a time, it will be difficult for that proof to be given. Courses of the type considered, where the duration is comparatively long, the output of students relatively small, and the expressed purpose essentially of a long-term character, cannot be expected to produce their full effects on industry immediately. For their worth to be proved beyond doubt and for the proof to attain wide recognition, both time and an assured flow of students of the right quality are necessary. In the meantime there lies the difficulty that for these courses to prove their value a supply of students is essential, whilst until that proof is forthcoming, industrial concerns may hesitate to lend their support. In terms of men, that support represents the release for a few months of but a minute proportion of the graduate engineers in employment, and, in relation to the potential long-term benefits, the cost to industry can only be regarded as infinitesimal. To a university, on the other hand, the maintenance of a graduate school of first-class quality represents a relatively heavy commitment which is unlikely to be continued for long without evidence that the full co-operation of industry will eventually be forthcoming. It is for this reason that the interest and backing of engineering firms and of the Government establishments during the early stages of the scheme is particularly desirable.

In certain quarters the fear has been expressed that to release a specially promising young man to attend a course of the type considered is to invite his thereafter being attracted to other employment. That this fear should be realized, however, is unlikely except as a result of the sense of frustration in one who, after arduous and concentrated efforts to improve his knowledge and ability, finds that no use is made of his added powers. The remedy is obvious and indeed, in the wider view, the

transfer in such circumstances of a good man from one firm to another involves no loss to industry as a whole and may even prove to its advantage. The argument quoted above has been used in the past in relation to the provision of facilities for the practical training of engineering graduates. Thus, to the short-sighted view, it appeared unreasonable that trouble and expense should be incurred in training young men for the possible benefit of other employers. Time and the lead given by certain far-sighted engineering firms have shown the unwisdom of this attitude, with the result that today excellent opportunities for the acquisition of practical training and experience are available, to the undoubted benefit of industry as a whole. As in this case, so in others. The one factor which above all else will decide the position of British engineering in relation to its competitors in ten or fifteen years' time is the quality of the young men of promise now coming forward, who will then be in control. In the long-term view, the preparation of these men for future leadership is a matter of supreme importance which deserves careful thought and constructive planning. Any steps taken now to improve their abilities and powers will yield future benefits out of all proportion to the temporary effort and inconvenience involved. Of the means available to this end, not the least important is the development of the full potentialities of a comprehensive system of advanced courses of instruction of the types outlined in the foregoing remarks. The task is one which calls for concerted efforts on the part of the university schools of engineering, the technical colleges and engineering firms. Each of these has an appropriate part to play, but it is abundantly clear that no efforts on the part of the two former bodies can be of avail without the active support and co-operation of industry itself.

Part III: Part-time and short-duration full-time courses

by Willis Jackson

1. Introduction

It is proposed to interpret the words "Advanced Courses" to mean courses of lectures, and their associated private studies, for prospective professional engineers which are supplementary to, and will in general be attended subsequent to, those which lead to the satisfying of the educational requirements of the professional institutions. In fact some of the courses which will be referred to will not be advanced in the strictly academic sense, since their purpose is that of assisting the young engineer to gain an appreciation and understanding of relevant features of engineering practice and industrial organization. They are nevertheless advanced in so far as, with university graduates, for example, they occur at an advanced stage of their preparation for professional status.

The examination regulations of the professional institutions aim to ensure that the candidate for professional status has acquired a sound knowledge and understanding of the principles of engineering science, as related, in the first instance, to engineering as a whole, and in the later stages to the particular field of engineering—civil, mechanical, or electrical—in which the candidate intends to spend his career. Although in the later stages the examinations in each case touch upon the specialized branches into which the practice in the three fields of engineering has become subdivided, they wisely give little encouragement to concentration on one of these branches to the exclusion of reasonable attention to the others.

Indeed events since the 1939–45 war have emphasized the need for increasing breadth in this educational preparation by revealing the intimate dependence of progress in one branch of technology on the achievements in others, and of technology as a whole on progress in the physical, chemical, and metallurgical sciences and in mathematical technique. It is not surprising therefore that the three institutions have found it necessary to keep their examination requirements under continuous review so as to ensure that this situation is reflected in the obligatory part of the educational preparation of the future professional engineer.

Since it is desirable, as a general rule, that this obligatory part should be completed by the age 22–23 years, there are severe limitations on what subject matter can be included in it. Inevitably there lies ahead of the successful student an immense accumulation of further knowledge. With varying degrees of relevance to different men, it concerns the engineering science of their chosen field, the techniques of the various specialized aspects of it, the materials on which the successful exploitation of these techniques is based, and the analytical tools which are nowadays available for application to the solution of engineering problems. Moreover, those for whom the basic educational preparation has taken the form of a university course will be embarking on their practical training and they must gain an appreciation of how and why, on economic as well as technical grounds, existing practices and organization have emerged and of the directions in which improvement is required and can most profitably be sought.

Until recent years the acquisition of this supplementary knowledge was left largely to individual initiative. It is now widely recognized, however, that this arrangement will no longer suffice, and steps have been taken to ensure a more effective dissemination of the specialized knowledge and experience available through the organization of appropriate advanced courses. We shall be wise to appreciate, nevertheless, that the previous situation was by no means lacking in merit.

It is true of course that the approach to a new subject is facilitated by critical presentation of the essential features of it, and from a co-ordination of the knowledge in the subject with that in related ones, by an expert. But it is of the greatest importance to recognize that this constitutes only the first part of the job.

In the absence of considerable personal initiative and prolonged self-sustained effort by the student himself, no amount of attendance at formal lectures will ensure real understanding of the information supplied or facility with its application to new and difficult problems. Very little will be achieved if the lectures do no more than hand out information. Their purpose should be to stimulate discussion, and to guide subsequent personal effort by the students—and their real value will be determined by the extent to which these objectives are achieved.

This paper is concerned with part-time and short-duration full-time courses, a wide range of which have been organized since the end of the 1939–45 war and are available in most large industrial areas. An attempt to make a comprehensive survey of these over the whole field of engineering, or even within electrical engineering, would be largely unprofitable, and has therefore been confined to the courses with which the author has been personally associated in one way or another. The discussion will no doubt correct the defects of this limited analysis.

2. Lecture courses as an integral part of graduate training

The Practical Training Committee of the Institution of Electrical Engineers has recommended that the practical training of electrical engineering graduates should be composed of three parts: (1) basic workshop training; (2) general mechanical and

lectrical training, and (3) directed objective training. The suggested durations of hese parts are four to six months, eight to twelve months, and eight to twelve nonths respectively, depending on the circumstances of the training organization md the needs of the individual.

The aim of the basic workshop training is to give the graduate the opportunity to ain familiarity with the uses and limitations of the principal hand and machine tools, nd to become acquainted with the properties of the materials used in electrical ngineering practice and with the related factors governing their application. deally, the initial part of this training should be conducted under intimate supervision in a special workshop set aside for the purpose.

The period of general mechanical and electrical training which follows widens this nanufacturing experience in suitably chosen production, test, development, and lesign departments. It prepares the graduate for a decision, in consultation with is supervisors and the senior staff members of the organization, as to the functional ctivity—research and development, design, manufacture, installation, or sales—to which the objective phase of his training should be directed, and also as to the particular product with which this training is to be associated.

A typical graduate training scheme operated on these lines within a large electrical ngineering firm in Manchester incorporates four groups of lecture courses as follows (Birtwistle 1955)*:

.. *General lecture courses extending over the first eight months of training*

The initial two months of basic training are spent in the workshop of an apprentice raining school. Six hours per week are devoted throughout this period to lectures nd discussions on the principles governing machining, fitting, welding, foundry, and pattern-shop practice, and on the structural, magnetic, and insulating materials n general use in the main factory. These courses are followed by a drawing-office class of 16 weeks' duration and occupying 2 hours per week. Its purpose is to acquaint the graduate with the firm's drawing-office organization and practice, with the importance and the problems of standardization, and with the standards in use n the concern.

Overlapping the latter, and extending over a period of six months, 2 hours per week are devoted to two series of "functional" and "product" lectures, with associated discussion, presented by senior members of the company's staff. The first of these courses is intended to afford a broad insight into the nature and organization of the research, design, production, and sales departments, the essential relations between them, and the structure and operation of the firm as a whole.

The majority of graduates have little difficulty in deciding with which of these functions they will wish to identify themselves on the completion of their training, and therefore towards which the objective phase of this training should be directed. They appear to experience more difficulty in deciding upon the particular product, such as turbo-alternator plant, motors, switchgear, control equipment, transformers, meters and instruments, electronic and radio equipment, scientific apparatus, etc., to which the exercise of their chosen function should be related, and therefore upon the product department under whose sponsorship this final period of training should be conducted. During their basic workshop and the general mechanical and electrical training they will normally spend periods within one or other section of

* Birtwistle, B. 1955 Metropolitan-Vickers Gazette, September, "Engineering Courses in Post-Graduate Training".

four or five of these product departments, and be given as much freedom of choice of them as is practicable. The purpose of the "product" lectures is to supplement and widen these contacts. The individual lectures are normally given by the chief engineer concerned, and representative members of the departmental staff are available to assist him in answering questions during the supplementary works visits. The apprentices are encouraged to develop the personal associations formed in this way with a view to assisting them to decide upon their product interest by the end of the first year of training.

2. *Applied mathematics course (first year)*

It is not perhaps surprising that during the early stages of the transition from academic to industrial life many graduates experience difficulty in seeing the relevance of their highly theoretical engineering education to the highly practical activity of their new environment. Some of them will of course neither wish nor need to maintain, let alone extend, their knowledge of mathematics and their acquired facility (if it be facility) in its application. On the other hand, for those interested in a career in research, development, or design, this is essential, though they will be wise to appreciate that mathematics can play only a limited, though it is a powerful, part in the solution of the complex problems with which the engineer is confronted.

To assist these men, a four months' course in applied mathematics is provided. It runs in parallel with the functional and product lectures and occupies 4 hours per week of which 2 hours are in works time. The course is organized largely on a tutorial basis, and involves a considerable amount of supplementary private study. The overall assessment of each man's work is made available to his training supervisor, who takes account of it in advising upon his second-year training programme.

The lecturers and tutors for the course are members of the company's engineering and research staff, the tutors normally being junior engineers who have themselves attended the course previously, and the lecturers more senior men who in the normal course of their studies are engaged on work requiring advanced mathematical knowledge and ability.

3. *Advanced engineering courses (second year)*

Only those who maintain a high level of performance in the first-year applied-mathematics course are permitted to enter one or other of the five second-year advanced-engineering courses referred to below.

Four of these courses, dealing with power system analysis, electrical machines, control system analysis, and radio engineering, are organized in collaboration with the electrical engineering department of the Manchester College of Technology, and occupy one day per week at the college over a period of 20 weeks. Some parts of the four courses are common—for example, series of lectures on numerical analysis, field theory and the principles of operation and the application of general-purpose digital and analogue computers, the network analyser and the electrolytic tank. Each incorporates the consideration of problems of current industrial significance. Again the courses are organized largely on a tutorial basis and require a considerable amount of private study.

The lecturers and tutors are drawn about equally from the college and company staffs, with assistance from that of the electrical engineering department of the university in one of the courses. The close collaboration between academic and industrial engineers engaged in the same fields of work which these arrangements involve is proving highly beneficial to the staff and students alike.

The mechanical engineering graduates are catered for at present by a company-organized course which deals with the main analytical methods of value in the solution of mechanical engineering problems.

. Courses in industrial administration (first and second years)

Reference was made in section 1 to the steps taken in the early stages of graduate training within a particular concern to ensure that he gains a broad appreciation of the structure and organization of the firm. Inevitably as his training proceeds this preliminary knowledge is strengthened and broadened by his active participation in the work of the company. For those whose interests lean towards the manufacturing side particularly, it is desirable, however, that this personal experience of a particular industrial situation should be supplemented by systematic study of the general principles of industrial organization and administration so that they may be the better able to assess the merits and limitations of the methods with which they are directly associated.

To cater for this need, the Industrial Administration Department of the Manchester College of Technology has arranged a sequence of lecture and discussion courses extending from October to May as follows:

First year—two evenings per week:

- Principles and practice of management
- Personnel administration
- Development and design
- Production and sales organization

Successful completion of these courses affords exemption from the Section C examination of the Institution of Mechanical Engineers.

Second year—one half-day per week:

- Industrial structure
- Industrial law
- Industrial psychology

. THE SCHEME OF "POST-ADVANCED LECTURES IN ELECTRICAL AND MECHANICAL ENGINEERING" ORGANIZED BY THE MANCHESTER AND DISTRICT ADVISORY COUNCIL FOR FURTHER EDUCATION

Most of the large technical colleges in Britain arrange courses of lectures and laboratory work in extension of those constituting their Higher National Certificate courses. These are repeated from year to year and satisfactory completion of a group of them, occupying several evenings per week for one year, lead, for past students of the college, to the award of the Associateship of the college. They are frequently attended by university graduates who wish to extend their knowledge in particular branches of engineering science.

The foundation in Manchester in 1936 of the Regional Advisory Council for Technical and other forms of Further Education (now known as the Manchester and District Advisory Council for Further Education) led to consideration of the need in that area to supplement these provisions by short, non-recurrent, courses of lectures dealing with recent developments in specialized fields of engineering work for the benefit not so much of students, as normally understood, as of experienced practising engineers. The discussions within the Advisory Council resulted in the setting up of an Engineering Advisory Committee composed of representatives of the local technical colleges, university and industry and of the Institutions of Electrical and

Mechanical Engineers, and to the introduction in 1938 of a scheme of Post-Advanced lecture courses. A particular feature of the scheme, which has proved of great merit, is that of associating with each course, as organizing lecturer, an acknowledged expert in the subject, with the responsibility for choosing his associate lecturers and of ensuring that their respective contributions are properly co-ordinated.

The subjects and durations of the courses arranged for the 1955–56 session are given in Table 2 and are representative of the arrangements in previous years.

TABLE 2.—POST-ADVANCED COURSES FOR SESSION 1955–56

Subject	No. of lectures
At the Royal Technical College, Salford	
Steam turbines	11
Aircraft stressing	12
Fuel efficiency and heat conversion	9
The development and utilization of modern mining electrical equipment	9
Electrical equipment of aircraft	8
Modern railway signalling	8
Field plotting techniques in engineering studies	8
At the College of Technology, Manchester	
Work study	8
Pressure vessels	8
Cooling towers	6
Linear network synthesis	6
Colour television	8
The application of digital computers to accountancy, costing, and managerial control	8

4. SHORT-DURATION FULL-TIME ADVANCED COURSES

Part-time courses of the type discussed in the preceding section suffer from the limitations that they afford inadequate opportunities for effective discussion and that they cater only for a local demand, whereas particular subjects may be of much more widespread interest and importance. These restrictions are removed by the alternative arrangement of a full-time course of a few days' duration which may be attended by men drawn from the country as a whole. A number of such courses have been organized by the Electrical Engineering Department of Imperial College of Science and Technology during the past few years, their subjects being:

Power system analysis
Electrical machine analysis
The insulation of electrical equipment
The electrical equipment of aircraft
The application of computers to the solution of engineering problems

Each of the first four courses was of five days' duration, and the fifth of ten, and the attendance of about seventy persons in each case was drawn in varying proportions, and mainly by nomination, from manufacturing industry, electricity supply, government establishments, and the universities and technical colleges. The lecturers were mainly from outside the college and the procedure adopted was to invite their co-operation some eighteen months prior to the proposed date of the course. During the intervening period a succession of meetings was held for the

purpose of defining the scope and content of the individual lectures and of ensuring that the subject matter of these lectures was available for circulation to the intending participants a month or so before the commencement of the course. In consequence, they were able to come well prepared for the discussion periods of which the course was mainly composed. These provoked extremely valuable exchanges of experience and opinion and, on occasions, led to the clarification of important technical difficulties. The content of the first and third of the courses appeared subsequently in book form and is therefore available for the benefit of future students of these subjects. In the author's opinion there is much scope and need for more courses organized on these lines.

5. Staff courses

It is a big step from satisfying the examination requirements of one of the professional institutions to the attainment of senior executive positions on the design, research, manufacturing, commercial or operating sides of engineering work, and this involves much more than profitable participation in a training scheme and in courses of the types described above. The only effective way of ensuring that a man can carry responsibility is to put him in a position where he is obliged to carry it. In no other way can he demonstrate convincingly the possession of certain essential personal qualities and abilities. When this has been demonstrated by success in one situation, he will be tested and matured in others of greater complexity, with the advice and example of his more senior colleagues to guide him.

Nevertheless, a great deal of thought has been given during the post-war period to the question of whether anything can be done outside the immediate environment of employment to assist this process. Can anything be done, for example, to develop a man's ability to appreciate the significance to his own work of the activities of others working in related fields; to organize co-operative effort among men of whose respective specialisms he may have only limited detailed knowledge; to draw reliable deductions and make sound decisions on inadequate evidence and in insufficient time; and to represent the views of other people, as well as to express his own, clearly and concisely.

Many experiments have been made during recent years in the attempt to seek answers to this kind of question, and it will help to focus discussion if a recent example is cited of a staff course of two weeks' duration for a group of 24 men in the age range 28–40 drawn from the research, design, manufacturing, sales, accounting, and overseas sections of a number of associated electrical companies. The aim of the course was not to instruct, so much as to enable the participants to compare their experiences and opinions and to evaluate these against a wider background than that of their individual environments.

For this purpose the topics chosen for consideration were, in the main, ones of which the members collectively had considerable experience in a variety of situations, and these were studied by the "Syndicate" method. The 24 men were divided into three groups of 8 men, each representative of as diverse a range of experience as possible, and to each of which an experienced tutor was attached. The tutor's function was that of consultant rather than of instructor, and to advise and guide, not to direct, his group's discussions. The composition of the three syndicate groups remained unchanged throughout the course, and each member acted as chairman for the consideration of one of the chosen subjects, and secretary for another. For each subject, the groups were supplied with a brief and referred to relevant reading material; they were also addressed collectively by a visiting speaker

TABLE 3.—ADVANCED COURSES OFFERED BY UNIVERSITIES

University	Department	Title of course	Duration
University of Birmingham	Mechanical Engineering	Graduate School of Thermodynamics and Related Studies	1 year
— do. —	Engineering Production	Principles of Engineering Production and Management	— do. —
— do. —	Industrial Metallurgy	Graduate Course in Metallurgy	— do. —
— do. —	Civil Engineering	Highway and Foundation Engineering	1 year (commences October 1956)
— do. —	Chemical Engineering	M.Sc. (Chemical Engineering) by Examination	— do. —
— do. —	— do. —	M.Sc. (Chemical Engineering) in Biological Engineering by Examination	— do. —
— do. —	Mining	Coal Preparation	— do. —
— do. —	Geology	Post-graduate Course in Applied Geophysics	— do. —
— do. —	Mathematical Physics	Post-graduate Course in Mathematical Physics	— do. —
— do. —	Physics	Reactor Physics and Technology in the School of Nuclear Engineering	— do. —
— do. —	— do. —	M.Sc. Course in Radioactivity	— do. —
University of Cambridge	Engineering	Theory of Structures and Strength of materials	1 year
— do. —	— do. —	Control Engineering	— do. —
University of Durham	Mechanical and Marine Engineering	Certificate in Production Engineering	— do. —
— do. —	Civil Engineering	Courses for Diploma and Certificate in Public Health Engineering	— do. —
— do. —	— do. —	Highway Engineering and Traffic Study	— do. —
— do. —	— do. —	Certificate in Structural Design	— do. —
— do. —	Electrical Engineering	Diploma and Certificate in Applied Electronics	
— do. —	— do. —	Diploma and Certificate in Electrical Power Engineering	— do. —
— do. —	Agriculture	M.Sc. (Agricultural Engineering)	2 years

University	Department	Title of course	Duration
University of Edinburgh	Faculty of Science	Diploma in Electronics and Radio	1 year
— do. —	— do. —	Diploma in Technical Chemistry	— do. —
University of Glasgow	Mechanical Engineering	Applied Thermodynamics	— do. —
Imperial College of Science and Technology (University of London)	Civil Engineering	Structural Engineering	1 to 2 years
— do. —	— do. —	Concrete Technology	— do. —
— do. —	— do. —	Hydro Power Engineering	— do. —
— do. —	— do. —	Hydraulic Engineering and Fluid Mechanics	— do. —
— do. —	— do. —	Engineering Hydrology	— do. —
— do. —	— do. —	Highway Engineering	— do. —
— do. —	— do. —	Public Health Engineering	— do. —
— do. —	— do. —	Soil Mechanics	— do. —
— do. —	Electrical Engineering	Applied Electron Physics	1 year
— do. —	— do. —	Communication Systems and Network Theory	— do. —
— do. —	— do. —	Electrical Machines and Power	— do. —
— do. —	— do. —	Power System Engineering	6 months
— do. —	Physics	Technical Optics	1 to 2 years
— do. —	Mechanical Engineering	Applied Mechanics	1 year
— do. —	— do. —	Gas Turbine Technology	— do. —
— do. —	— do. —	Heat transfer, Combustion and Heat Exchangers	— do. —
— do. —	Aeronautics	Aircraft Structures	— do. —
— do. —	Chemical Engineering	Chemical Technology	— do. —
— do. —	Chemistry	Inorganic Chemical Analysis	1 to 2 years
University of Leeds	Civil Engineering	Diploma in Concrete Technology	1 year
— do. —	Chemical Engineering	Diploma in Advanced Study in Fuel Technology, Gas Engineering, Chemical Engineering, Ceramics, Metallurgy	— do. —

TABLE 3—continued

University	Department	Title of course	Duration
University College of London	Chemical Engineering	Diploma in Chemical Engineering	3 terms
— do. —	Civil and Municipal Engineering	Diploma in Surveying	1 session
King's College (University of London)	Chemical Engineering	Diploma in Chemical Engineering	1 year
University of Reading	Physics	Diploma in Technical Physics	1 session
— do. —		Agricultural Chemistry	1 year
University of Sheffield	Post-graduate School in Applied Mechanics	Applied Mechanics	1 year (divided into five-week courses)
— do. —	Metallurgy	Physical Metallurgy	— do. —
University of Southampton		Diploma in Electronics	1 session

who later participated in the final conference on the subject. At these conferences the three relevant syndicate chairmen outlined the agreed or contradictory views of their colleagues on the subject in question, and these opening speeches were followed by the general discussion of an agenda which had been prepared by the chairman and secretaries of the syndicates in consultation with the three tutors.

The time-table for each syndicate subject comprised two syndicate meetings, the address by a visiting speaker followed by a discussion, a third syndicate meeting and the final conference, each of $1\frac{1}{2}$ hours' duration. The aggregate time of $7\frac{1}{2}$ hours was supplemented for the syndicate chairman and his secretary by that occupied in private reading, consultation and the preparation of scripts. Special importance was attached to the last of these activities, and this accounted for the inclusion in the programme of the subject "The Spoken and Written Word" and for the considerable time devoted to it. The topics chosen for syndicate discussion included Company Organization, Wage Structures, Productivity, Trade Unions and Employers' Associations, Uses and Limitations of the Figures Normally Presented to and Used by Management, and Economic Background. Many other allied subjects would no doubt have been equally well suited to the achievement of the objectives discussed above. Arrangements were also made for talks on related matters by senior executives of the organization, or by experts from outside it, and for subsequent discussion of them by the course members as a whole.

Only after a long succession of these courses will it be possible to make a reliable assessment of the benefit accruing from them, and the author would welcome the opinion of those who may have more extended experience of their organization.

Acknowledgements

The author wishes to express his indebtedness to Professor E. Bradshaw and his colleagues at the Manchester College of Technology for their co-operation in the Advanced Engineering Courses referred to in section 2; to his late colleagues at the Imperial College of Science and Technology, and particularly to Mr M. W. Humphrey Davies, for organizing the courses described in section 4; to Mr H. Taylor of the Administrative Staff College, Henley, Mr B. C. Brookes of University College, London, and Mr D. A. Clark of the Imperial Tobacco Company, for their invaluable assistance in the planning and administration of the staff course discussed in section 5, and also to many company colleagues, notably Mr B. Birtwistle and Mr B. W. Burnett.

The Paper is not open to Correspondence.—Sec.

Discussion

Mr G. S. C. Lucas said that the three Papers threw light on separate facets of collaboration between the universities, technical colleges, and industry. Successful collaboration was necessary not only for the future well-being of the engineering industry, but also for the healthy growth of technological education.

Speaking of continued engineering education and training, Professor Mucklow had said that "except in so far as short term aspects are concerned, engineering firms in general remain as yet unconvinced of the existence of the problem and still less of its urgency". Mr Lucas considered that it would be fairer to say that the formula for successful collaboration had yet to be worked out. The engineering industry, or at least the electrical

engineering industry, for which he could speak with more authority, was very conscious of the problem and of the need to find a successful solution.

Professor Mucklow had suggested that the best form of collaboration was for industry to send back to the universities men who had already had several years of industrial experience, in addition, of course, to 2 years' practical training and 2 years' National Service. Many of those young men were already in responsible positions. Obviously, if they could be spared to return to the universities for one or two years they might learn much, but it was open to discussion whether the amount they would learn would justify their prolonged absence. Similarly, if young men of the same age and ability who had chosen an academic career could be spared from the university for one or two years in industry, they would learn much, especially those who had never been in industry. But the national manpower shortage had to be taken into account, and advanced post-graduate courses planned to suit existing conditions.

Apart from the difficulty of releasing students for such courses, proposals for collaboration would have to take into account the fact that much of the specialized knowledge that should be included in advanced courses was in industry. There was a great deal in the larger firms and smaller amounts elsewhere, and the whole needed to be integrated into courses with the universities' contribution.

Therefore he suggested that at least for the time being expansion of the courses described in Section 4 of Dr Willis Jackson's Paper under the heading of "Short-duration Full-time Advanced Courses" should be envisaged. The list given in the Paper had already been extended and, more recently, there had been a 3-month course on Electrical Power System Engineering which had covered a great deal of ground. It was an excellent example of the co-operation between a university college and industry, not only in the preparation of the course and the provision of lecturers, but also in the release of students of the right standard and in the right numbers. It was a concentrated course. It meant that everyone who attended had to work hard and had to do "homework". It was a course which might easily have been spread over 12 months if the difficulty of releasing men from industry for longer periods had not been realized and taken into account.

Professor S. J. Davies said that the advanced courses to which he would refer were those given to more senior officers of the Army, who were released from their normal duties for lengthy periods in order to improve their usefulness by study in specialized courses. At the Royal Military College of Science at Shrivenham, in addition to some 200 young officers reading for London University Degrees, prospective Technical Staff Officers, aged about 30 and upward, from all arms and from the more important Commonwealth countries took advanced courses in specialized branches extending generally over 1½ years. To enter the course a suitable degree or its equivalent was necessary, but officers not so qualified took a preliminary year, making 2½ years in all in which to cover the basic subjects represented by a degree. Incidentally, that course had followed a similar one called the Advanced Class, which had been conducted when the College was at Woolwich, from 1864 to 1940.

Naturally, the conditions under which serving officers were released from duty to study were not applicable to professional engineers, but the seriousness of the need for engineers to be released for diversified types of courses was underlined in the three Papers under discussion. As a nation, Britain had long been too complacent and too satisfied with the three academic years, amounting to about 90 weeks, in which to give engineers the fundamental side of their training. Her competitors had all allowed a much longer period and, to meet the demands of modern developments, she must be prepared to supplement that short period for a proportion of graduates. He considered, nevertheless, that the present system should be adhered to and supplemented with advanced courses as they became necessary, since experience at Shrivenham had shown that they were more effective when given to men with considerable practical experience. There was a big difference in the points of view of young officers and those returning after eight or more years of army duties. The young officer was in a favoured position, in that if he did not get a degree he

id not lose his job, and at first he was indifferent. Then he became interested and did more work; but was still inclined to do the minimum necessary to get a degree. On the other hand, the older men coming back had often to be prevented from overworking. They were over keen. The points of view of the young graduate and the experienced man were very different.

The range of special subjects in which an engineer in practice might wish for advanced courses was very wide. A small proportion might require the comprehensive courses, taking an academic year, outlined by Professor Mucklow, but many more required shorter courses. For those, Mr Morgan had made the practical suggestion that employers of young engineers should count on their being absent during one or two weeks of a year attending advanced courses of one kind or another. The pioneering spirit of Dr Willis Jackson's company still existed, and the care given to training their graduate apprentices was admirable. But those measures were possible only in a large organization situated in a very large city.

Dr Willis Jackson had described the Staff Courses and the working of syndicates, which brought up the important question of the nature of the courses best suited to advanced students. He himself considered that too much emphasis was placed, both in undergraduate and advanced courses, on an active delivery of instruction by lecturers and teachers and a more or less passive reception of that by their pupils. Further, the ability of advanced pupils to contribute mutually to a study and the interplay of ideas between the members of a group were rarely sufficiently exploited. The syndicate system had gone far to correct that.

The Paper brought out the need for some new thinking on the important matter of the organization of, and the methods employed in, advanced courses. Love* had made a cogent plea for a systematic investigation into methods employed in undergraduate courses and, in particular, had criticized the ability of graduates to apply their knowledge in practice. He hoped that one result of the joint meeting would be that the three senior engineering institutions would take the initiative in bringing about the kind of research which Love had advocated, and in extending that to advanced courses.

What was being done in other countries should be noted, but, as a result of the considerable time and study he himself had devoted to various continental systems, he was convinced that such an investigation should be concerned primarily with British methods, which had to conform to traditions and characteristics.

Mr R. G. Bellamy said that Mr Morgan had *inter alia* defined some of the skills of the executive. He made no apologies for restating those in his own words since it allowed him to comment on a number of points raised by the contributors.

The executive had to keep abreast of technical developments—i.e., technical in its broadest sense—scientific, commercial, financial, and administrative. Then he had to have the ability to direct the work of others, some of whom might be specialists in fields other than his own. Next he had to acquire an understanding of the economic factors affecting his organization, both local and national. He had also to have the ability, in consultation with others, of preparing plans which would eventually mature into policy decisions, and present those clearly and succinctly, both in writing and verbally, to top management. To do all those things well meant he had to have a sound appreciation of staff relationships.

Professor Mucklow had dealt with the first of those skills, i.e., the ability to keep abreast of the technical aspect of the job. It was known that a number of post-graduate schools had been formed in Britain. Also that post-graduate work was being provided in technical colleges. Indeed, he would say that what was provided in technical colleges was better known than that in universities. Universities, like barristers and doctors, hesitated to advertise their wares. He would have welcomed from Professor Mucklow an indication of the post-graduate schools and their aims, particularly from the engineering standpoint. It was significant that in his own industry twelve adult scholarships were awarded a year

* *Love, P. P.* 1956 *Proc. I.Mech.E., vol.* 170

and never once had there been an application to take a course in a post-graduate school although there had been applications to do individual pieces of research. He thought that the universities should be less shy and should approach industry as did other post-graduate schools. For example, the National Gas Turbine Establishment, the College of Aeronautics, and the Reactor School at Harwell were offering post-graduate courses of which industry was aware.

Still dealing with the development of scientific skills, his industry had had the co-operation of a number of universities in the running of specialist courses for personnel of the industry on such subjects as the 275-kV grid, power system analysis, and protective gear. Whilst he appreciated all that was being done, it was probably true to say that it was not the role of the universities to run anything in the nature of bread-and-butter courses, but rather to establish principles and, by experiment, develop a curriculum for a course and then leave it for the technical colleges to provide as required.

Some of the other skills of the executive enumerated above could be developed to some extent by courses of the type referred to by Dr Willis Jackson as staff courses. Many of those present would recognize in them the executive development courses now run by a number of organizations. The Administrative Staff College at Henley ran the *de luxe* version, lasting 3 months, the British Institute of Management one of a month's duration, whilst several industries ran their own particular varieties. The whole principle of that type of course was one of participation in a creative sense by the course members rather than the established lecture *cum* discussion technique. Syndicates were given projects to thrash out, and members' thinking was stimulated by visiting specialists, reading, discussions, and visits. There was no claim that such training made the top-grade executive. In fact the training experience was only an additional aid and the principal contribution would come from experience on the job itself. The value of job rotation for the executive under training was too obvious to discuss in detail.

There was possibly some value in training staff in the art of self-expression, making a verbal case, stating a point of view. His own industry had developed courses in "Communications" with that intention in mind. Others included it with executive development training.

Dr J. E. Richardson said that some comments had been made about the volume of work which was being undertaken on the courses, and the number of students who attended them. He would ask whether that represented success or failure.

During the current year no fewer than 49 courses had been organized, with an average attendance of 43 students per course. The maximum number on any one course had been 64 and the minimum number 4. The previous year the comparable figures had been 33 courses with an average attendance of 34 students. He asked whether that represented success or failure. It was most valuable that Dr Willis Jackson should have uttered a word of caution to the effect that counting heads and the number of people taking courses did not necessarily mean that they had absorbed what they had heard.

He had with him a few pamphlets which bore a variety of titles, and again he asked the question, whether or not success was being achieved. He would ask what was wanted. One pamphlet was entitled "Automation in the Factory" and another "Operational Research". It had transpired that 130 had attended the course for "Operational Research" and 16 for "Automation in the Factory".

There was also the problem of communications. He wondered whether colleges could discover the real need and make the necessary provision. Through the Regional Advisory Councils something of the industries' needs in a district could be learnt, but his own experience was that they did not ask for more than about 10% of their needs and that was putting the figure rather high. Professional institutions very rarely stated the courses that were needed, and industry never did so. So the colleges made a guess on a somewhat hit-and-miss basis. The Head of the Mathematics Department had first heard of the course on Operational Research on the Third Programme! Sir Owen Wansbrough-Jones had given a lecture on the Third Programme and, as a result, no less than 130 people had

joined the Operational Research course! That was his first point: how was the need to be discovered.

Secondly, supposing the need was discovered, he wondered how the colleges could effectively advertise the provision which they had made. Advertisement in the technical and ordinary Press was expensive and not too effective. It could be done by direct communication with individuals and firms, but that also broke down. Personnel managers might not be responsible for research development and therefore would not hear about it. The Education Officer might not deal with people over 21 years of age, and many factories were scattered and communication was only with headquarters. Then the lists of names to be written to might be correct for one subject but of no use for new subjects. It was done by notices in professional journals and by letters to members of professional bodies. In the case of Operational Research the Operational Research Association had told their members, who had told their friends, and they had all joined. It was really a problem of communication: "you telling us what you want and we telling you what we have".

Reverting to Dr Willis Jackson's warning that inducing people to listen to lectures might not be an indication of a meeting of the real need, he hoped that the alternative was not the only pattern for the future, because he recalled putting on a series of lectures on Metrology which had led to the formation of a Metrology Association whose members had met every month, and it had been in existence for many years. Therefore, it would appear that sometimes people who attended and listened to lectures did want to carry on with the subject.

Professor E. Bradshaw said that the general refresher course helped the man who had to take responsibility for, but not work actively in, a given field. He believed that such courses also had a value in helping the readjustment of those whose way of life was likely to be disturbed by new processes.

Then there was the class of person who required treatment of a specialized field, and for those a short week-end course, where it was possible to meet others and to gain knowledge not only from the lecturer but also from the other people working in the same field, was better than a course spread over eight to twelve evenings.

The longer course, generally of from 2–3 weeks to a month or two, obviously permitted the tutorial approach which became more desirable the higher the level of the work attempted; but he considered that caution should be exercised in introducing the long course too freely.

Many courses would be more effective if greater care were taken in the choice and in the limitations to the scope of the topic concerned. Again, care should be taken in the selection of those attending. That could not usually be done by a directive as to who should and who should not attend, but effective control could often be gained by making clearer the aims of the course, its scope, and the desirable qualifications of those attending.

He referred to the publication of course material mentioned by Dr Willis Jackson. His experience had been that fear of the additional work which might be involved, if publication was intended, might deter lecturers from assisting with such courses.

His own view was that the courses which were organized by the full-time teacher tended on the whole to be more coherent than those organized by someone in industry.

He would like to confirm Dr Richardson's point that the Engineering Advisory Committees seemed to have great difficulty in obtaining suggestions from industry as to what were its real needs.

He confirmed Dr Willis Jackson's belief that the course for electrical engineering graduate apprentices in their second year of training (Section 2, p. 492) was proving effective. In the second year of its running laboratory work had been introduced, and that had been found most effective, particularly as in such a group of men there were physicists and mathematicians who had not previously been in adequate contact with laboratory practice. In that particular course the selection and preparation of students was well done, because in their first year they had had basic lectures on mathematics and other subjects which had enabled an appropriate selection to be made, and that had

enabled the starting point to be known roughly so that the best use could be made of the 20 weeks of one day a week.

Dr W. J. Gibbs said that he wished to support all that Dr Willis Jackson had said, particularly regarding the effort required from the students themselves. Unless the men were made to work hard the aim was not attained.

He and his colleagues had found the implications in some of Professor Mucklow's remarks rather disturbing. They agreed with the separation of advanced courses into two main classes, the specialist courses catering mainly for the current and the immediate future and the general courses of an advanced nature looking to the more distant future. The specialist courses had been, and still were, supported by his company on a very large scale, and they were, in general, satisfied with the results; but for the type of course with which Professor Mucklow was chiefly dealing, which provided for a comparatively small number of selected men in order to give them a deep insight into theory and a familiarity with advanced concepts, they preferred to do it themselves for the present at any rate.

Most undergraduates stored their knowledge into well-defined compartments, and on coming into industry they tended to keep those compartments tightly closed. They learnt to manage without developing the methods of analysis and thought which they had assimilated. The fact was that it was possible, even in design and research, to do without advanced theory exactly as had been done in the past, by using basic theory and engineering intuition. It was surprising how quickly engineers developed that intuition and, once they had acquired it, there was little incentive to acquire the much more difficult art of applying advanced theory to practical problems. Yet that art was necessary for any real progress to be made.

Their own advanced engineering course had been running for 9 years and they had accumulated a large amount of experience. The main object of the course was to impart the advanced concepts of engineering in such a way that the student was helped to bridge the gulf which usually lay between theory and practice. That required applicational lectures as well as lectures on advanced theory. Applicational lectures were given by men on the staff who had in the past themselves applied advanced theory to actual problems. Lectures on advanced theory which linked up with applicational lectures were given by a small staff who provided continuity for the course and who supervised the private study.

Professor Mucklow had advocated for that type of course full-time study in an atmosphere of freedom from the distraction of industry, and to support his thesis he had made some statements which were hardly merited. For instance, he held that the highest possible standard of teaching was necessary, and he had put that in such context as to imply that that high standard was available only in universities. He would not comment on that! He had stated that to teach at that advanced level required in the teacher himself the habit and background of study at advanced level. He himself agreed but would suggest that teachers in industry did possess that habit and background; in regard to research to which he had also referred, select teaching staff when not actually engaged in teaching duties were, in fact, deeply immersed in the research problems of the company. He considered that when courses of that nature were organized by the university they should be either on a part-time basis as in industry, or should be concentrated into a full-time course of one or two months' duration.

Mr M. L. Meyer referred to Professor Davies's remark that the viewpoint of students using the opportunities that were being offered was conspicuously missing, and he wished to support the plea that the students be asked for their contributions. The personal view of one student, though valuable and important, obviously was not sufficient, and research should be undertaken by questionnaire in order to obtain a comprehensive picture from the opinions of a large number of students.

He also supported the suggestion made in recent discussions that the engineering Institutions should interest themselves in such research. In the Post-graduate Department of Applied Mechanics in the University of Sheffield a review was normally made at

ıe end of a course and the students were asked to criticize and make suggestions. Clearly, ıore valuable results would be obtained from an investigation made by a neutral agency ne or two years after the student had returned to his industrial post and had found how uch the course had helped him in his work.

The post-graduate courses described by Professor Mucklow owed their origin to the ncouragement given by the Universities Grants Committee in their "Note on Technology . Universities" issued in 1950. Although five years was a short time in which to establish a teaching tradition, much had been done at a great number of universities and olleges, and industry was entitled to demand more than a plea for support, namely, proof work done and of opportunities offered now and in the near future, i.e., of opportunities at took into account present difficulties of securing and holding adequate technical staff r current work, let alone future projects. It was a great pity that Professor Mucklow ad not described the valuable and interesting work being done in Birmingham, and that had not at least summarized the great variety of courses offered already at many niversities. It was a variety not only in subject-matter but also in aims, arrangements nd duration of courses all too little publicized.

He would briefly mention some of the work done in Sheffield, not because they regarded e work there as outstanding compared with similar work done by their colleagues at the mperial College or in courses on other engineering subjects given in Sheffield and elsehere, but simply because there had not been the time for an effective comparison of otes to be made for the purpose of the discussion.

Like Professor Mucklow, they preferred students to stay for 9 or 12 months but, underanding that industry could not spare many people for such a long time, they were repared to arrange their subjects so that courses of 5 weeks' duration could be taken with lvantage. Professor Mucklow's standpoint regarding the subdivision appeared to be too ealistic as a general statement under existing conditions. They might revert to it when dustrial conditions and their own success warranted it.

They were an entirely separate department under the direction of Professor Tuplin nd had instituted their own research projects, although main emphasis had to remain on aching. The fact had forced them to develop a combination of industrial and academic search which they believed to be of great value.

Working in a separate department, their students had less contact with the general udent population. They had to provide for the lack, by creating a self-contained mmunity, not only technically but on a general intellectual level. They could combine at with attempts to foster a pioneering spirit which they believed to be as important for e application of knowledge as was their teaching activity.

At present much of the work of the mentioned Department was done in prefabricated ıts conveniently grouped together. That arrangement, and the fact that the Department was rather cramped for space, tended to assist the development of a community irit that was at once educational and enjoyable. They hoped, and sometimes found atifying evidence, that their students gained a little more inner freedom during their ay and work in the Department.

The age of their students averaged 28 years. There were 10 full-time students and 35 ining one or several 5-week courses during the current session. The numbers tended to crease steadily, a sign of healthy development at the present stage; 60% were sent by ivate industry, and students came from places ranging from Southampton to Glasgow d from overseas.

In addition, they had not refrained from taking the academic standpoint into factories d giving lectures as well as demonstrations to firms willing to sponsor them in their ctories. That tendency not to remain within their own building would find another tension in the mobile laboratory for which the Universities Grants Committee had cently given a generous special grant to the department, and which was nearing completion. Demonstrations in factories, field investigations into loads, stresses, vibrations, d noise, and non-destructive testing would also help students to see more clearly the nnexion between academic and industrial research methods.

Within the walls of the universities the use of existing available equipment by or in the interest of industrial firms, and the ensuing desirable collaboration, might well receive an impetus from the Universities Grants Committee's decision to encourage establishment of electronic computing centres in five centrally situated universities. Their own Post-graduate Department was excellently suited for such collaboration in research and experiment, and they invited firms sending employees to their courses to use the Department's equipment for industrial problems and even, if the problem was suitable and important, to have special equipment designed by the sponsored student and built by the Department in collaboration with the firm. The student would receive guidance from the Department's staff and be able to obtain specialist advice also from other departments of the university; the firm would have the advantages of the results of the research and of a member of staff returning fully conversant with all the problems involved. They welcomed contact with past students socially and in matters of technical problems of common interest.

That was an example of what universities could do and were doing, in many cases. In the development of an industrial product there was the paper stage, the pioneering stage, the prototype stage, and full-scale production. They believed that the problem of graduate training in Britain had passed the paper stage. The pioneering stage was fully developed, as Dr Willis Jackson's and their own experience had shown. It was time to collect and relate the various pioneering reports and to base further action on an evaluation of them and perhaps on research on the lines suggested by Love.*

Such an evaluation would have to take into account experience in other countries. It was no secret, for instance, that graduate training had been developed to a very advanced stage in Soviet Russia, and that Western observers had remarked on that as an essential element of Russian technical advance.

Thus the problem was not only academic and technical but also political, and a decision must be reached in time on the basis of all available evidence, even if incomplete. The piecemeal approach adopted in the papers, excellent as they were, was unlikely to produce all the available evidence in the time still available before action must be taken by Her Majesty's Government.

Mr M. W. Humphrey Davies said that his remarks would be confined to a few suggestions concerning the contribution that universities and large technical colleges could make to the advanced training of engineers in industry. He would not draw any distinctions between universities and the larger technical colleges for that was too controversial.

It should be remembered that the primary function of universities was the intellectual development of their undergraduates, and carrying on that work in the post-graduate field in training scholars and research workers. That might sound pompous, but it was important.

Dr Willis Jackson had referred to the short-duration full-time advanced courses which had been started when he had been the head of the Electrical Engineering Department of Imperial College. Experience with those courses and others had confirmed that there were several ways in which the universities could contribute and which would be of great benefit to both parties, provided courses could be arranged so that they did not take up too much of the time of the universities' staff and, at least under present conditions, provided they did not distract people from work in industry.

In considering the shorter full-time courses, a distinction should be drawn between survey courses and teaching courses. By "survey courses" he meant those which were intended to act as a stimulus in bringing to the notice of engineers methods which had recently been developed and which were about to become available. The people attending those courses were generally experienced in the work concerned and Imperial College had been very fortunate indeed in the support which had been given by industry in arranging that kind of work. For that kind of work the 5-day courses had proved very suitable indeed, but for certain types 3-day courses were equally good.

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* See footnote* on p. 501.

The 5-day period had been shown to be very suitable, and for providing practice in, as ell as information about, new methods, a period of 2 weeks seemed to be the absolute inimum, and he himself was sure that a 4-week period would be much more suitable.

In general they had found that that teaching course should be limited to 20 or 30 ersons, but up to 70 might be accepted for the survey course.

The longer course in the university, lasting 3, 6, or 12 months was a very much more fficult proposition. Imperial College was fortunate in having D.Sc. courses which were ainly attended by students from overseas, although one or two satisfactory experiments ad been made with non-graduates who qualified in Britain. The course occupied 2 years which the first 6 months were spent in attending lectures in laboratory work, and for verseas graduates that had been found to be essential. It did not, however, help in-ustry, and recently that had been studied, and he thought that it should be possible to an a course lasting 3 months which would attract a few men from industry and which ould be linked up with the one-year course for graduates from overseas, and which might so be linked up with research projects carried out jointly in universities and industry.

Those were matters for the future to which thought must be given, and with which at mperial College they intended to experiment as much as possible.

Mr B. J. Tams said that he would like to add a few remarks to Dr Willis Jackson's art of the Paper, because he had more recently been connected with the heavy electrical dustry. Throughout that industry the 2-year graduate apprenticeship had much in ommon. They happened to prefer the initial 3-month period spent on basic training in orkshop technology at the local technical college where such subjects as "Materials and rocesses", "Use of Machine Tools", "Drawing Office Practice", "Fundamentals of anagement", etc., were taught in a course specially designed for university graduates. he remaining 9 months of the first year were spent in gaining general factory experience, aching a point at which functional and maybe product selection could be made. They elieved that individual assistance from specialized tutors was valuable from that stage nwards. Men were generally divided into small groups during the second 12-month eriod when they received considerable assistance from senior engineers. That second ear frequently consisted of an initial few weeks of full-time lectures in the field required, llowed by 8 or 9 months of appropriate factory experience, concluding with a few weeks advanced lectures from senior executives in that branch of the industry.

He thought that industry was doing a great deal in the matter of post-graduate courses. hey had organized no fewer than twenty-five courses during the past 12 months for men ell beyond their apprenticeship, and they had found that it was often convenient to hold ach courses during the early evening, partly in the men's time and partly in the company's me—say, from 5 to 7 p.m.

With regard to mathematics, industry was finding that it was worthwhile to continue ving special tutorial work in advanced mathematics to suitable graduate apprentices roughout their training.

As to Arts graduates, they too had been encouraged by experience gained, that certain en could be trained for semi-technical administrative work in industry. It was clear at men of fine personality were freely available and posts were being found for those en in purchasing, storekeeping, office administration, personnel, and similar work.

On the question of training for general administration, they placed great value on sidential courses within the company. Their own particular version happened to be of weeks' duration, fully residential and using the syndicate basis in certain aspects. romising young men were regularly drawn from the various factories within the Group meet top senior executives on such courses.

Mr J. F. Coales said that evidently all were agreed that the real problem was to rovide senior executives who had a technical background and a technical appreciation.

The three types of course that had been mentioned in the discussion were needed by all, ut he suggested that the evening courses and the short courses were of much more value

in training experts and specialists than in helping men to become senior executives. That he thought was largely because not only had the advanced theory and practice to be taught, but also something psychological, an attitude of mind in the application thereof.

In Cambridge there were two full-time courses, one which had been going for some considerable time in civil engineering, with which he was not personally concerned, and during the current year a full-time course had been started on control engineering.

Another reason why it was necessary to have long-term courses was that in industry the conscientious engineer—and all the best engineers had to be conscientious—whenever he was working on a problem, was seized with the urgency of finding a solution, and that tended to make him put on intellectual "blinkers" while solving it. He tended therefore to specialize, and it was very difficult to prevent that having a very narrowing effect on the engineer. He himself had tried when in industry to overcome that narrowing effect with the best engineers by sending them on short courses, to evening classes, to summer schools, and to conferences. It had had some, but not sufficient, effect. It had not had the necessary effect with some outstanding engineers. If they were sent back to the university on approximately a year's course to study some subject which had a fairly wide field, and which covered more than one aspect of their particular branch of engineering, it would be seen that it would have a broadening effect. They also would have time to study other subjects, to discuss matters of common interest with colleagues, and that would have a very marked effect in broadening their outlook.

One of the advantages of control engineering which was evolving as a new subject was that both electrical engineers and mechanical engineers had each to do a considerable amount of the other engineering and also some chemical engineering. An attempt had been made to teach the basic principles of those during the first term but it had not been entirely successful. Many mechanical engineers had found a knowledge of electrical circuits and electronics very difficult to grasp, which was causing some concern as to how sufficient time could be found. But it seemed to be showing good results in broadening their outlook.

They were well aware that it was easy to teach even advanced theory compared with teaching the application of it in industry. They were also well aware that when the students went back to industry they would seldom have to use the advanced theory which had been taught them, but there would be some occasions when they would need to use it, and it might be equally important to teach them when not to use it. At any rate, an endeavour was made to instill proper judgement in the use of advanced methods and to provide practical work so that how to apply both simple and advanced theory was learnt, how to work frequently with inadequate tools, and how to improvise. To accomplish that it was evident that a full year was necessary. They had had students for most of the vacation, which had put a heavy load on the staff, but it was necessary because during the term there was not sufficient time to give several days to an experiment. In the vacation that was possible, and it had already proved to be of very considerable value.

Professor F. K. Bannister said that the growing awareness of the problem facing British industry in regard to post-graduate engineering education was evidenced by that joint meeting of the nation's three great Institutions and the very acceptance of the problem was a major advance.

His own special responsibility during the past 5 years had been the Graduate School of Thermodynamics and Related Studies associated with Professor Mucklow's Department in Birmingham. His more particular interest, therefore, concerned the role of what had earlier been termed the full-scale university graduate course.

The case for part-time post-graduate training, whether provided by technical colleges or industry itself, could hardly be overstated. Supplemented by short full-time courses of the summer school variety, it could afford an effective and rapid means of propagating technical knowledge, particularly where the latter concerned separate and self-contained items or comprised techniques and practices peculiar to the firm sponsoring the course. Properly developed and extended, those part-time arrangements would provide adequate

pportunities for the vast majority of graduates in industry to keep pace with current ractice in their firms.

That, however, was not in itself enough. Unless development was to proceed merely ong well proved and traditional lines, the technical leaders of the future required a good eal more and it was in that respect that the universities were so peculiarly well fitted to lp. In a number of chosen fields of engineering they already offered established aduate courses, the aim, in general, being to deal with advanced-level fundamental inciples rather than details of current design practice. The object was thus, within the nits of the field concerned, to achieve a general-purpose tool of maximum versatility and ırability rather than a range of special-purpose ones for immediate but restricted use.

To produce an abiding understanding of the advanced theoretical concepts of a number related subjects within the field, and of associated techniques in the laboratory, required me—a great deal of time if the coverage was to be comprehensive and the depth worth nile. In consequence, the minimum duration of courses of that type was often a whole ssion.

The question was often asked, and understandably so, "Could not these courses be vided up into a series of shorter periods of, say, 2 months' duration, each self-contained ıd dealing with one particular facet of the full syllabus? This would allow of the short-rm secondment of graduates from industry without any major interference with their ıties." He could not speak as to the general impracticability of such subdivision, but t strongly that where the content was fundamental in character, as was the Thermo-namics School at Birmingham, such a piecemeal presentation would render the course mpletely ineffective in so far as its main purpose was concerned. The value of the course y largely in the integration of the various subjects, the frequent cross-bearings and inter-lationships between them and, above all, in the possibility of devoting a considerable riod at the outset to the revision and consolidation of the students' earlier theoretical ıowledge. In their own experience, because the graduates were drawn from a number different universities and, in addition, usually had several years' absence from academic ıdy, at least 5 weeks must be spent in bringing them to a common level from which they uld proceed to the more advanced concepts of the graduate school proper. The need r such an introduction was in itself a sufficient indication that, in certain types of course least, subdivision was not the answer to the problem.

The difficulties of industry in releasing men for the long-term courses must not be under-timated, but it must also be remembered that such courses were intended only for the ry few. The men for whom they were designed comprised only a minute fraction of e graduate population of industry, and there had been encouraging signs over the past to 3 years that more and more firms were prepared to forgo a man's services for 9 or 12 onths in the belief that the eventual dividends would amply repay them for their mporary inconvenience.

Those acts of faith must at all costs bring forth from the universities the very best that ey had to offer. No half measures or improvisation would suffice, and the very least at industry could expect was a properly constituted intensive programme of well-lanced lectures, experimental work and tutorials, the whole being under the personal ntrol and guidance of one whose sole duty that should be. Given hard work, en-usiasm, and enterprise on both sides, there was no doubt as to the eventual outcome.

Mr P. P. Eckersley said that he had engaged a large number of staff during his etime. In fact, he had engaged the staff which had founded and maintained British oadcasting as the paramount system of the world, and he remembered those men who d now been honoured rightly and widely.

A little later on when he had left the B.B.C. he remembered being discouraged by seeing number of experts in series, and had said to a friend "I shall ask the next one who is s favourite poet, and I shall engage him even if he says Dobson"!

There was a contrast, and he would say that that was because those who had been erested in engineering in the early days had been men of broad general culture. They

had been lucky because the numbers had not been so great then; but listening to t[illegible] discussion he would proffer the thought: whether the current tendency was to ma[illegible] experts and try to make men of them afterwards and whether it would not be better [illegible] make men first and experts afterwards.

He thought that it was very important in the formative years of a man's life to have [illegible] broad general education, because then he was intellectually trained to think of the relatio[illegible] ships of the different aspects of technology, science, and research, and he was the ma[illegible] who would eventually be able to handle people. He thought that it was very importa[illegible] to have a broad education in the early stages and add expertise to it afterwards.

** **Mr P. Burylo** wrote that a few years previously, being sponsored by an in[illegible] dustrial organization, he had undergone a year's Graduate Course of Thermodynamics an[illegible] Related Studies at the University of Birmingham, and therefore his views on that cours[illegible] in particular, and on graduate training in general, might be of interest.

The syllabus and general information of the course could be found in an official prospe[illegible] tus, and he would like to add some facts which he hoped would throw some light on th[illegible] value of the course.

Very rightly, emphasis was placed on the fundamentals, and when acquired they forme[illegible] powerful tools in the hands of an engineer who was faced with ever-growing new problem[illegible] and ideas. Often a single problem required advanced knowledge of several subjects suc[illegible] as Thermodynamics, Dynamics of Fluids, Heat Transfer, Dynamics, and Electronics. [illegible] "common language" for all those subjects was mathematics. Considerable time was spen[illegible] during the course to acquire a good working knowledge of advanced mathematics, whic[illegible] included vector analysis, relaxation methods, finite differences, La Place transform[illegible] matrices, etc. Lecture and experimental work included recent theories and techniques[illegible] They had a stimulating effect and kept students abreast with modern development. Tha[illegible] enabled them to read and follow technical papers and reports of an advanced nature[illegible] which in turn might lead to new ideas and improvements in design and manufacture.

One of the conditions of admittance to the course was that an applicant had to have ha[illegible] several years of industrial experience. It was an important point, for it enabled him t[illegible] find a problem for investigation, gave him a practical approach in experimental work, an[illegible] also showed him how insufficient his undergraduate course was and, consequently, th[illegible] necessity for further studies.

The course forged a strong and lasting link between industry and the university, whic[illegible] was beneficial to both sides. It was a friendly relationship. Often an ex-student dis[illegible] cussed his technical problems with a lecturer who, apart from his up-to-date theoretica[illegible] knowledge, had also wide industrial experience and could offer good advice. Such [illegible] discussion might lead him to valuable research work of practical importance.

Short-term courses, of a specialized nature, catered usually for the immediate needs [illegible] industry and the main task was an application of well-established theories, devoting ver[illegible] little time to fundamentals and theoretical background; therefore they were of little valu[illegible] so far as development of thinking power was concerned.

The value of a full-time graduate course could not be overestimated—but the trainin[illegible] was not complete at the end of the course. An ex-student needed guidance and help fro[illegible] senior engineers who were prepared to share their knowledge and experience with him[illegible] thus re-establishing the old principle of "master and pupil".

Professor W. Fisher Cassie wrote that his remarks were directed to the first tw[illegible] parts of the Paper and were strongly in support of Professor Mucklow's contention th[illegible] advanced courses to be effective should last 9–12 months, and occupy the full-tim[illegible] attention of the student. Mr Morgan's proposals, typical of the short-sighted policy no[illegible] informing British engineering, offered no objection to short-term courses of a dilettan[illegible]

** This and the following contributions were submitted in writing after the closure [illegible] the oral discussion.—Sec.

type, but did not even envisage adequate full-time courses. The greater part of his Paper was concerned with instructing educationists in technology how to conduct technological education. He had not even defined and certainly had made no real attempt at solving, the real problem in Britain—that of convincing industrialists that their young men and their not-so-young men must spend much more time at full pressure in keeping abreast of the current surging development. Only in the universities had engineers time to take the wide view and to pass on their findings through the techniques of post-graduate study and experiment.

To suggest "a week or two of study time in any year", "brief courses of lectures", "broadening the range of . . . evening classes", was merely to toy with a serious subject. A visit had only to be paid to the Technische Hochschule to see how close was the relation between German technical universities and industry, or to similar institutions in the United States of America to see how many of the post-graduate students were seconded on full pay from American industrial firms. Conversely, a visit had only to be made to post-graduate courses in Britain to see how relatively weak was the link between British universities and industry.

Post-graduate courses had been running, on the lines proposed by Mr Morgan, for a long time, and short courses were well supported by members of the engineering professions. In the full-time courses, however, a preponderance of yellow, black, and brown faces was found and if a white one appeared it usually belonged to a young man persuaded to stay on after his first degree before he became engulfed in industry never to return! The very few British engineers of some years' experience who returned to the universities from industry usually did so by giving up their jobs and suffering financial loss.

In the University of Durham, for 13 years, annual short courses on topical civil engineering subjects had been run, and it was clear from the enthusiastic attendances that there was a need for more popular refresher courses. In the full year's courses, however—Structural Engineering, Traffic Studies, and Public Health Engineering—all at real university level and all supported by Treasury money—the majority of the students came from abroad. The course in Public Health Engineering was so well known along the equator that it had had to be adapted to tropical conditions. During the 5 years that course had been running not one British practising engineer had been to study recent developments, although practising engineers had been seconded from such places as Costa Rica, Guatemala, and Singapore.

In a discussion of the expansion problems of Imperial College recently, a well-known engineering periodical had commented:

> "On the other hand, among those receiving the post-graduate award of Diploma of the Imperial College the number of foreign students, particularly from the Far East, was noticeable. This emphasizes one of the problems that the college is facing in its expansion plan. A large part of the additional facilities will be for post-graduate work, but at the present time, owing to the shortage of grants for such work, a majority of post-graduate students come from abroad. This is a problem to which industry and the Government will have to give increasing attention in the next few years."

There was no need to tell the universities what courses to teach. They were well in touch with modern developments and problems. What was required was that industry should realize that as taxpayers their members were supporting post-graduate courses of real value which were being taken by overseas students who returned to improve their home engineering on lines the British engineer was seldom allowed time to study. To say that Britain could not afford to let her best young men return to the university for a year at a time—the usual argument—was to imply that the technological competition Britain faced, from countries where universities and industry were strongly enmeshed, was not disquieting, and that we could advance without "monitoring", through our young engineers, the present world-wide technological developments. He would ask if that was really so.

Dr W. H. Glanville wrote that he observed that Mr Morgan had suggested that brief lecture courses might be run in conjunction with the "Open Days" which had been held at the Road Research Laboratory. It was an interesting suggestion, but in fact the Laboratory had gone very much farther than that in providing courses for road engineers and representatives of allied interests. During the past 10 years, seventy courses had been run at the Materials and Construction Division, and they had been attended by slightly over 2,000 representatives, drawn from the Ministry of Transport, county and urban highway authorities, consulting engineers, contractors, manufacturers of road materials, and from other Government Departments responsible for road and airfield construction; the latter included 270 engineers from Colonial Public Works Departments. In addition, at the Traffic and Safety Division, on the approaching completion of the fifth annual course, nearly 200 representatives of highway and police authorities would have attended courses on Traffic and Safety.

The duration of the courses had varied from 7 to 13 working days and, except for a few special comprehensive courses, the subjects dealt with at the Materials and Construction Division had been soil mechanics, bituminous (including tar) materials, and concrete roads. There were usually two courses in each subject per "session"; the demand for places had nearly always been greater than the number available. Although the organization of courses involved an appreciable diversion of research effort, he was satisfied that they provided an effective means of disseminating up-to-date information. Many members of the courses had said that only by being detached from their normal duties had they been able to get a thorough grasp of new knowledge; wide publicity in the form of official reports on the results of research was not so effective because the pressure of normal duties had left them no time for study. The number of engineers who had attended courses on behalf of highway authorities and road building concerns had represented only a very small proportion of the total who would be eligible to attend, but it had been clear that their influence within their respective bodies had been fairly considerable in many cases. Assistance had also been given by staff lecturers at courses organized by the universities and other educational establishments, and evening courses of six lectures had been given by a special staff lecturer at six major technological schools.

Mr H. D. Morgan, in reply, welcomed Dr Glanville's remarks and the interesting information given on courses for Road Engineers and representatives of allied interests at the Road Research Laboratory, and agreed that that, in fact, did go very much farther than the suggestions made in the Paper.

In reply to Professor Fisher Cassie, Mr Morgan wished to remark that he had no desire to attempt to instruct educationists in technology how to carry out their work. He could only judge their work by its results and had noticed that a very large number of men having recently graduated had been found to be very nearly useless in a practising engineer's office. He had in his time been warned of that by his own Professor of Engineering who took a somewhat different view from Professor Fisher Cassie and sent graduates out with the remark that when they arrived on the site of engineering works, they should remember that they would be of rather less use than a second-grade carpenter. He had found, somewhat to his surprise, that that was, in fact, correct.

He could not feel himself responsible for the condition of the civil engineering industry as set out in Professor Fisher Cassie's contribution, nor for the fact that many of the students were from abroad.

Professor Fisher Cassie apparently believed that the industry could afford to undertake the cost of sending large numbers of young men on long post-graduate courses at Durham University. That was typical of a point of view which appeared to have no contact with the realities of the engineering industry.

Dr Willis Jackson, in reply, said that by arrangement with Professor Mucklow he had restricted the subject matter of his part of the Paper to part-time and short-duration full-time courses, the need for and purpose of which seemed to be clear enough

and to be generally accepted. What was perhaps in doubt was whether many of those participating in the courses were supplementing their attendance with sufficient private study to ensure that full benefit was derived from them.

So far as long-duration full-time courses were concerned he had no personal doubt that while the present 3-year period of undergraduate study probably sufficed, and, if the entry standards could be maintained, would continue to suffice, for the majority of university engineering students, it would not do so indefinitely for *all* students—and indeed it did not suffice at the present time. He believed that there was much less difference of opinion on that point than there appeared to be. It seemed to him that the controversy revealed in the discussion arose more from (1) the insistence by universities that their post-graduate courses had to conform to the administrative pattern which had been laid down for undergraduate study, at a time of serious man-power shortage resulting from the rapid expansion of industrial activity and the operation of the military service regulations, and (2) lack of adequate discussion and agreement between the universities and industry on the precise objectives and most profitable content of particular courses. There was great need and scope for co-operative experiments between the universities and industry in that field, in extension of those outlined in section 4 of his part of the Paper. Out of those would undoubtedly grow in time adequately supported arrangements conforming more clearly to those proposed by Professor Mucklow.

At all costs complacency must be avoided. He had visited Russia a few months earlier and had been impressed by the immense scale of their educational effort. Very large numbers of young men, and girls, were following $5\frac{1}{2}$-year courses in engineering from age 17 to 18, and a few per cent of those were spending a further 3 years on advanced study and research in the educational institutions and the Research Institutes which were intimately associated with them, in many cases following a period of industrial experience. It was easy to draw wrong detailed deductions from casual observation of the educational systems of other countries, but since observing great vitality elsewhere it would be wise to ensure corresponding vitality in our own system through closer collaboration between all the parties concerned.

Professor G. F. Mucklow, in reply, wrote that he agreed with Mr Lucas that his references to the attitude of engineering firms towards the long-term aspects of the problem had perhaps been somewhat exaggerated. He was well aware that there were notable exceptions, especially within the electrical engineering industry, and had indeed been intentionally provocative, with the object of promoting discussion.

Although he had stressed the long-term advantages offered by the full-scale graduate school, he had emphasized also the need for a range of other kinds of course, of arrangement and duration suited to the particular objective. Of such, the type advocated by Mr Lucas was one example.

The difficulties of releasing men in responsible positions to attend full-length courses were obvious but he had been at pains to show that, by so releasing a few selected individuals, the long-term benefits could far outweigh any temporary inconvenience suffered. If that were not so, then such courses were doomed, but it was surely short-sighted to condemn them without fair trial.

Professor Davies's references to the advanced courses for senior officers held at the Royal Military College were most interesting. The rate of advance in the science and art of warfare and of engineering were parallel, and in both cases there was need for the long-term view.

He agreed with Professor Davies that the 3-year university period was all too short especially for the few destined for future technical leadership. It seemed logical, however, that, for such men, the additional theoretical training required should come after practical experience and when the field of their interest was known. Professor Davies's remarks on the keenness of older men returning to advanced courses was borne out by experience at Birmingham.

Mr Bellamy had referred to the advertising of University graduate courses. He

thought it probable that most universities circulated details of such courses to firms likely to be interested, as was the practice at Birmingham. How often such notices penetrated the outer defences and reached high authority was, however, open to question. Personally, he regarded quality of product as the only satisfactory and enduring form of advertisement and "Faith and Works" to be preferable to sales talk.

In response to the suggestion of Mr Bellamy and Mr Meyer, he had added Table 3 showing graduate courses offered by universities. The list had been extracted, not without difficulty, from information supplied by University Registrars and included only the full-length type of course. If there were errors and omissions, he trusted that those concerned would accept his apologies.

Dr Gibbs had reproved him for implying that the highest standard of teaching was to be found in the universities and technical colleges, i.e., amongst those whose job it was to teach. He remained unrepentant.

That the advanced courses organized within Dr Gibbs's firm had given good results over a period of years both evidenced their high quality and supported the general arguments of the Paper under discussion. There was usually more than one way of attaining the same objective, and he suggested that a comparison could be made only after a trial of alternatives. It must be remembered, however, that not all firms had the resources available to Dr Gibbs and his colleagues.

He had replied elsewhere to Mr Meyers's request for a summary of advanced courses offered by universities, but had not included the short-duration type of course, since such a list would be incomplete without reference to the courses given in technical colleges. He considered, however, that in present circumstances, it would be inappropriate to describe in detail the work done at Birmingham.

He noted that, at Sheffield, the graduate course had been split into separate sections of 5 weeks' duration, although a full period of 9–12 months was still regarded as the ideal. He considered that the adoption of that expedient would materially detract from the potential value of the course, for reasons mentioned by Professor Bannister. He was surprised that Mr Meyer considered the "splendid isolation" of his students to be advantageous. He himself took the opposite view, and considered that a student, whether graduate or undergraduate, had much to gain from membership of the university and participation in university life.

He was unable to agree with Mr Meyer in regarding research as suitable for inclusion in the curriculum of a graduate course of the type considered. The function of such a course was to teach the theories and treatments stemming from research, but he viewed the actual conduct of research by its students as evidence of a confusion of purpose. In any case, he could not understand how a student could profitably engage in research in a course lasting a few weeks.

He had been particularly interested in Mr Coales's remarks and fully agreed with him that, quite apart from its formal teaching, the full-length graduate course had much to offer to its students. The attitude of mind resulting from the study of a number of subjects related to the chosen field of interest, the discussions and interplay of opinion and argument within a group of men of varied experience and the participation in university life, all conduced to a broadening of outlook, the value of which could not lightly be disregarded.

He agreed with Mr Eckersley as to the importance to any man, whatever his profession, of the qualities which derived from a broad general education. The development of those attributes, however, depended on whether the seeds of cultural interests had been sown at their right season, at school and in the home, rather than on the profession adopted in later life.

Mr Burylo's communication was of special interest, since it expressed the views of one who had actually attended a course of the type under discussion. The experience detailed could not but bring encouragement to those responsible for the organization of such courses.

Professor Fisher Cassie's remarks on the interest in post-graduate courses shown by industrial firms on the European continent and in the United States of America were significant. He had faith, however, that the same situation must eventually obtain in Britain, provided only that the courses available were maintained at the highest possible level of quality.

ORDINARY MEETING

13 March, 1956

WILLIAM KELLY WALLACE, C.B.E., President, in the Chair

The Council reported that they had recently transferred to the class of

Members

Davies, Cyril Arthur Clifford.
Fowle, Frederick Edward.
Hall, Albert Claypole, M.Sc. (*Manchester*).
Henderson, Ian Farquharson.
Jeffery, Joseph Dennis Whitmore, T.D.
Kendal, John Taylor.
Moynihan, John Joseph, B.E. (*National*).
Orchard, Henry Cornelius.
Porter, Arthur Ronald, B.Sc. (Eng.) (*London*).
Tonks, Daniel James, T.D.
Walker, Robert Haigh, B.Sc. (Eng.) (*London*).
Williams, Owen Tudor, M.A. (*Cantab.*).
Wilson, Stanley Valentine, B.Sc. (*Belfast*).

and had admitted as

Graduates

Alstead, Robert Malcolm, Stud.I.C.E.
Barnett, Stanley Gordon.
Biggs, Cedric Ross, B.Sc. (*Witwatersrand*).
Bourne, William Stuart, Stud.I.C.E.
Brennan, Michael Joseph, B.E. (*National*).
Brierley, John Stewart, B.Sc. (*Glasgow*), Stud.I.C.E.
Bulman, John Neville, Stud.I.C.E.
Caldow, John Maitland, B.A. (*Oxon*).
Carter, John Michael, Stud.I.C.E.
Conacher, Michael Jim, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Crichton, Thomas Bryan, Stud.I.C.E.
Cuckney, John Herbert, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Davies, Bryan Lloyd, B.Sc. (Eng.) (*London*).
Dougan, William, Stud.I.C.E.
Dyson, Peter, Stud.I.C.E.
El-Khayatt, Ali Mohammed Hassan, B.Sc. (*Wales*).
Enslin, Stephanus Petrus, Stud.I.C.E.
Findlay, Peter James, B.Sc. (*Durham*), Stud.I.C.E.
Flint, Roy Alan, B.Sc. (Eng.) (*London*).
Fox, Russell Herbert, Stud.I.C.E.
Glennie, David Gordon, B.A., B.A.I. (*Dublin*).
Green, Harold, Stud.I.C.E.
Green, James Keith, B.Sc. (*Nottingham*).
Gubbay, Robert, B.Sc.Tech. (*Manchester*).
Haliburton, Derek John, M.Sc. (Eng.) (*Natal*).
Hall, Gordon, B.Sc. (*Wales*).
Hanson, Donald Alan John, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Hunter, Alvin Richard, Stud.I.C.E.
Jarosz, Josef Wojciech, B.Sc. (Eng.) (*London*).
Jeffries, Peter John, B.E. (*Tasmania*).
Jonnes, Sidney Philip.
Kafaru, Mudashiru Kokumo, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Kant, John Senior, Stud.I.C.E.
King, David, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Lees, Ronald, B.Sc.Tech. (*Manchester*), Stud.I.C.E.
Leeves, Geoffrey Gordon, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Lindsay, Denis, B.Sc. (*Belfast*), Stud. I.C.E.
McCulloch, Alexander Griffith, Stud. I.C.E.
Malcolm, James Graham, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Manners, Derek William.
Mills, James.
Montgomery, Hugh, Stud.I.C.E.
Moran, Patrick James, B.E. (*National*).
Murray, Donal Richard, B.E. (*National*).
Patel, Rasiklal Mansukhohai, B.Sc. (Eng.) (*London*).
Peters, Colin James, B.Sc. (Eng.), (*London*), Stud.I.C.E.
Pothecary, Colin Harold, B.Sc. (*Bristol*).

Ranatunga, Don Gamini Lakshman, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Rose, Alan James Elder, B.Sc. (*Edinburgh*), Stud.I.C.E.
Russell, Alan Turner, B.Sc. (Eng.) (*London*).
Smith, Robert Thornton, B.A. (*Cantab.*).
Soffe, Laurence John, Stud.I.C.E.
Staines, Malcolm, B.Eng. (*Liverpool*).
Steedman, James Cyril, Stud.I.C.E.
Stevenson, Colin Stewart, B.Sc. (*Glasgow*), Stud.I.C.E.
Stirling, John McClumpha, Stud.I.C.E.
Stuart, Alexander Alfred, B.Sc. (*Glasgow*), Stud.I.C.E.
Stutchbury, Richard Charles, B.Sc. (*Southampton*), Stud.I.C.E.
Tolcher, Raymond John, B.Sc. (*Bristol*).
Wallace, David John, Stud.I.C.E.
Warburton, Henry Brian, B.Sc. (*Bristol*), Stud.I.C.E.
Watson, Douglas Whitelaw, B.Sc. (*Glasgow*), Stud.I.C.E.
Whitehouse, Brian, B.A. (*Cantab.*).
Wilson, David Michael, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Younghusband, Gordon Edward, B.Sc. (*Manchester*), Stud.I.C.E.

and had admitted as

Students

Aggarwal, Subash Chander.
Aitken, Alan Dunsmuir.
Anderson, Alan John.
Assie, Albert Nicholas.
Barr, David Auchenvole.
Berridge, Hugh Bentall.
Bevan, John William.
Biggin, Richard Sumner.
Bishop, Colin Charles.
Bodoano, Richard John.
Booth, John David.
Borrie, John Alexander.
Bramwell, Jon Charles Anthony.
Buckingham, John Stewart.
Burrows, Geoffrey Edgar.
Carvell, Clifford Allen.
Chalmers, Alexander Paterson.
Couzens, Christopher David.
Croft, Maurice Bootheway.
Crossley, Brian.
Dennis, Jeffrey.
Devine, John Alexander.
Dougill, John Wilson.
Dunnicliff, Christopher John, B.A. (*Oxon*).
Eaton, Anthony Stuart.
Edey, Nigel David Charles.
Elvy, Michael Robert.
Fairhurst, Gerald.
Fairservice, Robin Andrew.
Farrar, David William.
Findlay, Donald Stuart.
Fisher, David Simpson.
Francis, Kenneth.
Gamble, Robert Graham.
Gibbs, Garry Keith.
Gill, Lewis Roger.
Gilson, George Edward.
Golden, John Edward.
Gow, Atholl Guthrie.
Grigg, David Brook.
Hamilton, John David.
Hannant, David James.
Harborow, Michael John.
Hargreaves, Peter.
Harrington, Brian Patrick.
Hayward, Derek Walter.
Hearsey, Geoffrey Richard.
Henderson, Ralph Murray.
Hill, Patrick Norman.
Holland, Richard George.
Hughes, Trevor Richard.
Humphreys, Dennis Whigham.
Hurst, Geoffrey.
Ibbitt, Michael Edward.
Jackson, Austin Victor.
James, David Arthur.
Jones, Eric Parry.
Jones, Martin Cunnick.
Keith, Charles Alexander.
Kenington, Harry Walmsley.
King, George Jeffrey William.
Kwasny, Zdzislaw.
Leigh, Jack.
le Masurier, Brian.
Lipscombe, Eric Richard.
Mabon, Walter Alan.
Macdonald, Alan Charles.
Mackenzie, Donald William John
McPhee, David.
Messele, Seyum.
Mills, David.
Moore, Ralph Richard.
Mouncey, Colin John.
Munro, John.
Pedley, Francis Hugh.
Phachonyutda, Damrong.
Potter, Henry Hugh.
Pybus, Philip John.
Pye, Derek Cave.
Reilly, Nicholas.
Richards, Francis Howard.

RILEY, RICHARD LOVELACE.
ROBINSON, BRIAN JEFFREY.
ROWLANDS, MICHAEL KEITH.
ST. ROSE, WILLIAM MAURICE.
SALMON, JOHN MICHAEL.
SHACKLETON, GORDON.
SHARMAN, MICHAEL THOMAS.
SHEARER, WILLIAM WALKER.
SHOJOBI, JOSEPH OLAWOLE.
SIMPSON, IAN.
SMITH, JAMES.
SMITH, JOHN CYRIL.
SPENCER, ROBERT.
SUTAN-TANON, NIPIT.
TATE, GEOFFREY MICHAEL.
TAYLOR, ALAN KEITH.
TELFORD, SYDNEY GORDON.
THIAGARAJAH, VISVALINGAM.
THOROGOOD, ANTHONY CHARLES.
TURNER, ANTHONY EDWARD.
WAKEMAN, MICHAEL JOHN.
WALES, ANDREW JAMES.
WARD, SIMON ROGER.
WATERMAN, ROBERT DENNIS.
WEAVER, JOHN.
WHITE, JOHN STEWART.
WILKINS, ROLAND.
WILLIAMS, DAVID LLOYD.
WILLIS, JOHN.
WOOD, RALPH.
WRIGHT, ANTHONY WILLIAM JOHN.

The following Paper was presented for discussion and, on the motion of the President, the thanks of the Institution were accorded to the Author.

Paper No. 6059

METHODS OF USING LONG-TERM STORAGE IN RESERVOIRS

by

* Harold Edwin Hurst, C.M.G., M.A., D.Sc.

SYNOPSIS

The investigation of long-term storage in reservoirs arose out of the study of schemes for the utilization of the waters of the Nile. It is based on probabilities derived from many cases of natural phenomena, principally rainfall.

A statistical equation has been previously given by the Author concerning the reservoir capacity which would have been needed on a stream to maintain a steady annual discharge equal to the mean for the period during which its discharge was recorded. This equation relates the capacity with the standard deviation of the discharge and the number of years in the period. The present Paper examines trial regulations for the use of the storage, which have been made on about fifty records of natural phenomena, of which three-quarters were rainfall or river statistics. It is known that many natural phenomena have frequency distributions approximately of the normal Gaussian form and this is shown in the Paper, where a combined frequency curve is given for about fifty natural phenomena, including most of those used in the trial regulations.

The trial regulations show the difficulties of regulating a reservoir for an unknown future, even when the past records of the available supply cover a long period. They also show the impossibility of doing so with any certainty if only this single set of records is considered, since it constitutes only one sample from a universe of phenomena with similar statistical characteristics. This Paper deals with a very much larger sample, and as a result of the trials a type of regulation has been found which will have the greatest probability of success when adapted to the special circumstances of a particular storage project. The continually increasing use of water resources makes storage problems not only more important but also more complicated.

Introduction

The relations between the capacity of a reservoir storing water over many seasons, with the inflow and its variability (standard deviation), and the draft from the reservoir have been previously established.[1] To obtain these relations long series of annual totals of river discharges from a number of stations were collected. For each series of observations departures from the mean were calculated and the accumulated sums of these departures were found year by year and plotted as a curve (see Fig. 1), with years as abscissae and accumulated departures as ordinates. A positive ordinate represents an excess and a negative one a deficit which would have accumulated if a constant discharge equal to the mean had been flowing. The difference between the highest and the lowest of these accumulated sums—i.e., the range R—is (a) the maximum accumulated storage when there is never a deficit; (b) the maximum accumulated deficit when there is never any storage; or (c) their sum when there is both storage and deficit. In the case where the maximum of the curve of

* The Author is Scientific Consultant, Ministry of Public Works, Egypt.

[1] H. E. Hurst, "Long-Term Storage Capacity of Reservoirs." Trans Amer. Soc. Civ. Engrs, vol. 116 (1951), p. 770.

accumulated departures from the mean precedes the minimum as in Figs 7a, 8a, 9, and 11 it is clear that R is the maximum deficit and, consequently, it is the storage which would have enabled an outflowing discharge equal to the mean to have been maintained throughout the period. In Fig. 1 the minimum preceded the maximum

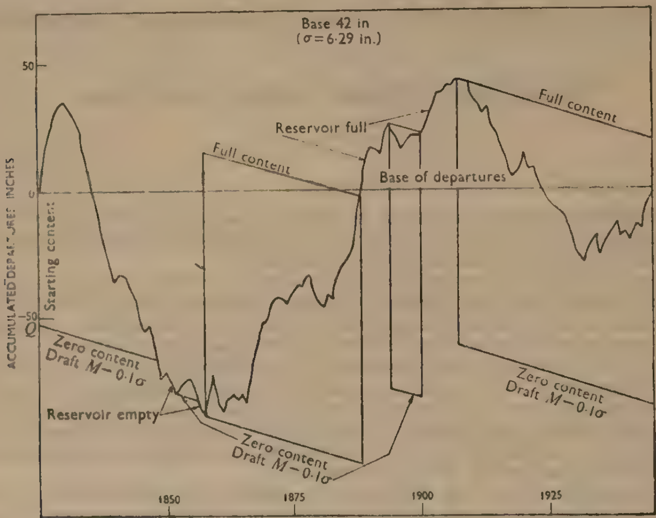

FIG. 1.—NEW YORK RAINFALL. ACCUMULATED DEPARTURES

and R is the maximum storage which could have been accumulated by keeping a steady outflow equal to the mean. In these calculations losses due to storage are ignored.

Similar calculations were made in regard to observations of rainfall, temperature, annual-growth rings of trees, and the annual layers of mud (called varves) which are deposited in lakes. In all R was computed from seventy-five phenomena whose records were divided into 690 series of years, varying in length from 30 to 2,000. All these phenomena showed a statistical similarity, namely that if the curves are plotted showing the frequency of occurrence of departures of different amounts from the mean, ignoring the order in which the departures occur, the curves which are found approximate to the Gaussian or normal frequency curve. This is shown later in Fig. 2 and in Table 2.*

The quantity R is obviously an important parameter in investigations relating to storage over long terms of years, and the greater part of the first Paper[1] was devoted to a discussion of this parameter. A short summary of the methods and results of this discussion were given in a recent Paper.[2] To make clear the *raison d'être* of the following account some important conclusions from the first Paper[1] are given here.

After the first few trial values of R were found it was thought that guidance in the determination of its form and properties might be obtained from a mathematical

* The Author has not investigated whether the statistical equations hold for distributions other than Gaussian.

[2] H. E. Hurst, "Measurement and Utilization of the Water Resources of the Nile Basin." Proc. Instn Civ. Engrs, Pt III, vol. 3, p. 1 (Apr. 1954).

nvestigation to find R in the case of random events, such as the tossing of coins. If set of m coins is tossed a number of times N, the number N being fairly large, it is nown that the average number of occurrences of m heads and 0 tails, $m - 1$ heads nd 1 tail, etc., are given by the terms of the binominal:

$$N(\tfrac{1}{2} + \tfrac{1}{2})^m$$

Also, the larger the value of m the more nearly does the frequency distribution pproximate to the Gaussian:

$$y = \left(\frac{N}{\sigma}\sqrt{2\pi}\right)e^{-x^2/2\sigma^2}$$

where y is the number of departures from the mean which lie between $x + \frac{1}{2}$ and $x - \frac{1}{2}$, and σ is the standard deviation of x.

The investigation showed that for such random events:

$$R = \sigma\sqrt{\tfrac{1}{2}N\pi} = 1{\cdot}25\sigma\sqrt{N}$$

It was found, however, by trial of a number of natural phenomena that R increased more rapidly than the theoretical value for random events. This is due to the tendency for natural events to occur in irregular groups in which high or low values preponderate. It was found by using such phenomena as the thickness of tree rings and varves, for which series exist which run into hundreds and even thousands of years, that R could be represented by a statistical relation of the form:

$$\log\frac{R}{\sigma} = K\log\frac{N}{2} \quad \ldots\ldots\ldots \quad (1)$$

The mean value of K, using ordinary logarithms, was 0·73 with a standard deviation of 0·09 and the extremes found in 690 cases were 0·46 and 0·96. The distribution of K was approximately Gaussian. This equation is to be interpreted, when the mean value of K is used, as giving the most likely value of R in any given case. From the variation of K just quoted it is clear, however, that values of R both larger and smaller than those given by the equation will occur. If $N = 100$ years the average value of R is $16{\cdot}7\sigma$. In the cases of rainfall given in Table 3, the mean is on the average $5{\cdot}2\sigma$, so as a rough guide R_{100} is of the order of three times the mean, but it may be considerably exceeded in extreme cases. One interesting point is that if the phenomena are divided into classes the mean values of K for the different classes do not vary very much, as Table 1 shows.

TABLE 1

Phenomena	Mean value of K
River statistics	0·75
Rainfall	0·70
Temperature and pressure	0·70
Tree rings	0·80
Varves—Lake Saki	0·69
Varves—Canada and Norway	0·77
Adopted mean	0·72

In calculating R departures are taken from the mean. If, however, departures are calculated from a base less than the mean, this corresponds to the case where the discharge out of the reservoir is equal to the base, except when the reservoir is full,

when the natural inflow passes. The maximum accumulated deficit S is the storage required to prevent the discharge falling below the base. The results of a number of computations of S for actual cases concerning rainfall, river discharges, temperatures, tree rings, and varves which have occurred gave a relation between S and B (the draft to be guaranteed), which can be represented by either of the following equations, both of which fit the observations equally well within their limits:

$$\left.\begin{aligned} \log_{10}\frac{S}{R} &= -0{\cdot}08 - 1{\cdot}05\frac{(M-B)}{\sigma} \\ \frac{S}{R} &= 0{\cdot}94 - 0{\cdot}96\sqrt{\frac{(M-B)}{\sigma}} \end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \quad (2)$$

where M denotes the mean of the observations. The feature of this relation is that a small difference of the draft from the mean makes a much greater proportional difference in the storage. For example, if $M - B = 0{\cdot}1\sigma$, then $S = 0{\cdot}65R$.

Although many natural phenomena have a nearly normal frequency distribution this is only the case when their order of occurrence is ignored. When records of natural phenomenon extend over long periods there are considerable variations both of means and standard deviations from one period to another. The tendency to occur in groups makes both the mean and the standard deviation computed from short periods of years more variable than is the case in random distributions.

In applying the results to actual practice, several difficulties arise owing to the facts that streamflow is variable and that we cannot foresee the future. Thus the problem of what storage is required and what draft can be allowed on a stream for the future is different from, and is an extension of, the problem solved in the previous Paper,[1] in which the events had already happened and the full data existed, so that trial regulations could be carried out until a satisfactory one was found. In the practical case of regulating an over-year storage reservoir the data which will exist will be the mean and standard deviation for a relatively short period of the past, but there will be no certain knowledge of how these will vary in the future. However, by statistical methods applied to the data used in the previous Paper[1] and by trying different regulations it should be possible to work out one which will have some assigned probability of success. This is attempted in the present Paper. The variations of the phenomena during the year are not considered and, together with variations of draft required during the year, must be dealt with separately.

Methods of computation

These will be briefly summarized here, since they were described previously.[1] For any phenomenon it is necessary to form the continued sums of departures (or the accumulated departures) of the annual values from a base, for which some convenient number close to the mean is chosen. These continued sums are then plotted as in Fig. 1 for the case of the annual rainfall totals at New York (mean 42, base 42) which is taken as an example. This curve of continued sums has the valuable properties that from it the mean for the whole period or any portion of it can be calculated and, also, the continued sums of departures from any base other than the one chosen, which are done quite simply.

In order to simplify the following description, all the statistics will be discussed as if they were river discharges and reservoir capacities. The accumulated departures of New York rainfall from the mean M are plotted for 120 years. An average value for R for 100 years is calculated from equation (1) which gives $R_{100} = 16{\cdot}7\sigma = 105$

in., and this is taken as the capacity of the reservoir. The value of R actually obtained from the diagram for 120 years is 132. The assumed draft which is to be tried is the mean M less $0{\cdot}1\sigma$ and the assumed starting content is $\frac{1}{2}R_{100} = 52$. This is shown on the diagram by a point to represent zero content 52 in. below the starting point of the curve. A line drawn from this point in a direction inclined to the base of departures at an angle $0{\cdot}1\sigma$ per annum represents zero content when the draft is $M - 0{\cdot}1\sigma$. The content of the reservoir at any time is represented by the ordinate of the curve above the zero-content line. After 23 years, in 1848, the curve crosses this line, showing that the draft has exhausted the reservoir and can no longer be maintained. The draft will then be the natural flow until this rises above $M - 0{\cdot}1\sigma$. This occurs in 1852, when the curve of departures begins to rise, showing that discharges are above the average. A new draft line is drawn to represent zero content and the content rises until 1855 after which the reservoir again empties, but from 1858 for many years the average discharge is well above the draft and by 1888 the reservoir is full. From then until the discharge falls below the draft the natural discharge must pass and the reservoir remains full. The discharge falls below the draft from 1890–1892, from 1896–1900, and from 1907 onwards, and the deficiency is made up from the reservoir, as shown in Fig. 1. If we want to know the mean discharge from 1908 to 1945, it can be derived from the difference of the accumulated departures at the end and at the beginning of the period, i.e., -1 and 43 giving a mean of 40·8 as follows. The accumulated departure from the base 42 at the end of 1907 is 43 and at the end of 1945 it is -1. There is therefore a decrease of 44 in the 38 years, an average decrease of 1·16 a year. The mean is therefore less than the base 42 by 1·16. This example shows the utility of the graphic method.

CHARACTERISTICS OF NATURAL PHENOMENA

The characteristics which concern us are:

(1) that the frequency distributions of annual values of many phenomena approximate to the normal Gaussian curve, when no account is taken of the order in which the values occur; and

(2) high or low values tend to be grouped together much more than in the case of random events.

Thus the long series of levels of the Nile recorded at Cairo show that there were times when the floods on the whole were high and others when they were low, but there is no obvious periodicity or other regularity.

With regard to (1) the frequency distributions used in the previous work will now be examined to see how closely they approximate to the normal Gaussian distribution. The method adopted was to express departures from the mean in terms of their standard deviations. The work was lessened by adopting a class interval of $0{\cdot}3\sigma$ for all the phenomena, giving classes of 0 to $0{\cdot}29\sigma$ and $-0{\cdot}3\sigma$ to $-0{\cdot}01\sigma$, etc., for departures from the mean. Then for each phenomenon these class limits were expressed as values of the phenomenon and the frequency in each class was determined from the actual annual values. The results of this are given in Table 2. A glance at this Table shows that there is no case where the distribution does not approximate to the normal or is more than slightly skew. The number of years included is not the same for each of the phenomena but varies from 59 to 211, with a mean of 116 (see Table 3). In all there are fifty-one phenomena and 5,915 yearly observations. The frequencies are added together class by class and are then reduced to a basis of parts per thousand. The results are plotted on probability

paper and are shown in Fig. 2. The phenomena are for the most part rainfall, but eleven cases of temperature are included. The latter are also plotted separately in the diagram. It will be seen that between departures of $\pm 3\sigma$ the curves are practically identical straight lines passing nearly through the point-departure 0, and 50%. Comparison shows that these lines approximate closely to the normal curve. The part which is normal includes all the observations except about two per thousand at both extremes. Outside this there is a sharp bend at either end in the direction of making the probability of large departures greater than they would be in

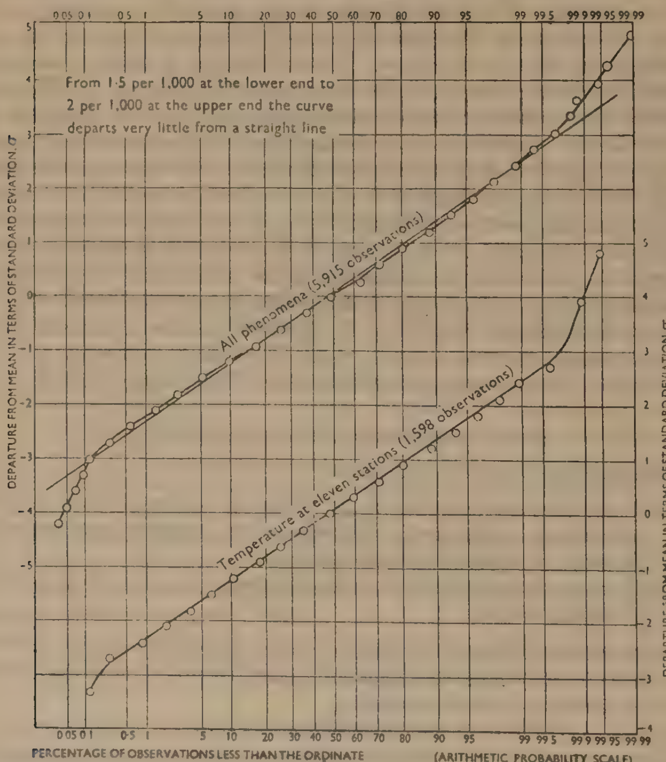

FIG. 2.—FREQUENCY DISTRIBUTION OF ANNUAL VALUES OF 51 PHENOMENA

a normal distribution. The extremes of the curve depend on a few observations, and of the two extreme departures of more than $4{\cdot}2\sigma$ at each end three are from the old records of Roda gauge dating from the Middle Ages. In the case of any records extending a long way into the past the possibility of mistakes cannot be excluded, and the effect of these, which is negligible in the classes which contain many observations, becomes considerable at the extremes of the distribution where the observations are few.

To sum up the matter; a sample of fifty-one individual phenomena has been taken mainly from the universe of annual rainfall totals (excluding small rainfalls) and mean annual temperatures. Examination of this sample shows that the fre-

quency distributions of its members approximate to the normal and that the total of the sample is very closely normal. Within limits determined by the statistical theory of sampling results found from this sample can be applied to predict what will happen to members of its universe in the future. This is the basis of the work carried out in this Paper and its predecessor. By showing that a phenomenon, e.g., the out flow from a catchment basin, belongs to this universe we can immediately widen our field from the properties of this single sample to those deducible from the much larger sample. The information from the larger sample consequently amplifies our knowledge of the phenomenon from which the single sample is taken.

With regard to (2), the grouping of high and low values, this has the effect of making the means and standard deviations much more variable than is the case with purely random events. As an illustration we may take the rather extreme case of Stockholm rainfall, which is recorded for 162 years, and divide the observations into four equal periods, then the means of these vary from 58 to 38 cm and the standard deviations from 13·5 to 7·8 cm. The occurrence of such runs does away with the old belief that a record of 30 or 40 years or more gave an average which was a close approximation to a true average, to which the phenomenon conformed. The fact is that there are no such fixed averages and the average of one 40-year term may be very different from that of the next, and the same applies to the standard deviation. The average and the standard deviation of a random event, such as tossing a set of coins, tend to constant values as the number of trials increases, but with natural events the average and standard deviation are relatively more variable, and the standard deviation has a tendency to increase with the length of the record. Whether it approaches a limit has not been investigated. This is shown in Fig. 3 where σ_1 and σ_2 are the

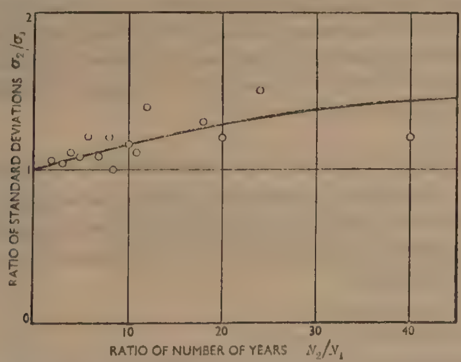

FIG. 3.—PHYSICAL PHENOMENA. INCREASE OF STANDARD DEVIATION WITH NUMBER OF YEARS OF OBSERVATION

standard deviations (average) for N_1 and N_2 years of observations of a particular phenomenon, and σ_2/σ_1 is plotted against N_2/N_1.

In what follows later, values of σ for 100 years are deduced from values for 30 years by multiplying them by a factor of 1·1, to have a little margin over the 1·05 shown by the mean curve.

METHOD OF INVESTIGATION AND RESULT OF A PRELIMINARY TRIAL

The regulation of a long-term storage reservoir on a stream may be for irrigation, supply of domestic water, flood protection, power, or navigation. In all these cases

the draft may vary with the time of the year, but this seasonal variation is not the concern here. The problem which has been investigated first is what system can be applied automatically to guarantee as large an annual draft as possible, but which will not empty the reservoir over a long term of years. It arose because of the need to make the greatest possible use of the Nile waters for irrigation by equalizing its flow and storing water for long periods. Flood protection is considered later.

To get an idea of the variation amongst different phenomena a preliminary trial (regulation 1) was made by the method already explained. The results were as follows:—

Regulation 1.—Capacity $R_{100} = 16{\cdot}7\sigma$ (σ for whole period); thirty-two phenomena; starting content $\frac{1}{2}R_{100}$; draft, mean of period, M. Reservoir filled in 66% of cases, emptied in 59% of cases. A result of this nature was to be expected from the fact that R is a mean value obtained from many cases. Filling or emptying might be prevented either by increasing the value of the capacity R, or by making the draft variable to some extent. A reduced draft was tried in the cases in which emptying occurred. The mean value of the reduction required to prevent emptying was $0{\cdot}16\sigma$ and the reduction in the worst case $0{\cdot}53\sigma$.

Regulation 2.—Starting content R_{100}; reservoir emptied in 41% of cases.

A regulation similar to 1 starting with the reservoir half full is an obvious one to try when both floods and droughts are to be avoided as much as possible. The second regulation starting with the reservoir full is better from the point of view of irrigation, if the necessity to pass the whole discharge (and so to spill water) presents no difficulty. There are, however, still cases where the reservoir empties and this, as explained, arises from the variability of the index K in equation (1).

In the above cases regulation takes place after the event, using the actual mean and standard deviation for the period. Even so, it is clear that a factor of safety is needed, and still more will this be the case when a mean and standard deviation from the past have to be applied to the future.

Regulations which would be possible in practice

To determine the regulations possible in practice the assumption is made that observations of the first 30 years are available and these are used as initial data on which to base the regulations, taking account of additional data as it accumulates. The following possibilities arise.

(*a*) The draft is kept constant.
(*b*) The draft varies with the inflow.
(*c*) The draft varies with the amount in the reservoir (content).
(*d*) The draft varies both with inflow and reservoir content.

The results of trying regulations of the above types are given in Table 4.

The sample of phenomena is a representative one, and for most the record covered more than 100 years. The above regulations suggested themselves as the work progressed to meet the difficult cases which will be discussed later. Table 4 shows that the larger the content the fewer the cases of emptying* and that a variable

* It is obvious that in theory the capacity of the reservoir could be increased so as to make the chances of its filling or emptying as small as desired. In practice, whilst this might be possible in some cases, in many others it would be impossible, either because of the cost or the occupation of land which is indispensable for other purposes.

TABLE 2.—ANNUAL VALUES. FREQUENCIES OF DEPARTURES FROM THE MEANS IN TERMS OF STANDARD DEVIATIONS
(Class-intervals in terms of standard deviations)

Phenomenon	N	−4·5 −4·21	−4·2 −3·91	−3·9 −3·61	−3·6 −3·31	−3·3 −3·01	−3·0 −2·71	−2·7 −2·41	−2·4 −2·11	−2·1 −1·81	−1·8 −1·51	−1·5 −1·21	−1·2 −0·91	−0·9 −0·61	−0·6 −0·31	−0·3 −0·01	0 0·29	0·3 0·59	0·6 0·89	0·9 1·19	1·2 1·49	1·5 1·79	1·8 2·09	2·1 2·39	2·4 2·69	2·7 2·99	3·0 3·29	3·3 3·59	3·6 3·89	3·9 4·19	4·2 4·49	4·5 4·79
Adelaide rain	112								1	1	3	4	15	10	10	10	19	10	7	6	8	3	2	1	2							
Albany rain	120									1	3	7	8	10	18	14	14	16	6	8	6	2	2	2	1	0	1	1				
Aswan discharge	80							1	0	0	1	7	5	12	14	3	7	8	1	8	5	5	2	0	1							
Bangalore rain	111							1	1	0	4	5	8	11	13	12	17	10	11	7	3	1	3	2	1	1						
Barbados rain	73								1	1	1	3	8	4	12	10	9	3	7	3	5	2	2	1	0	1						
Batavia rain	67										2	6	4	6	5	7	7	4	8	5	5	4	3	1								
Boston rain	128									2	2	5	9	12	17	20	14	13	6	9	7	3	5	2	1							
Calcutta rain	117								1	1	4	5	4	9	16	23	13	11	7	6	3	6	4	3	1							
Cape Town rain	111										1	2	15	12	13	9	18	9	11	4	4	4	4	2	1	0	0	2				
Charleston rain	114									1	1	8	11	9	5	17	23	11	7	6	4	5	1	2	0	3						
Cherrapunji rain	59									2	2	2	4	9	5	7	5	5	7	4	3	3	0	0	0	1						
Colombo rain	61										1	4	5	5	6	11	7	8	4	2	2	3	2	0	0	1						
Dalalven level	176								2	2	5	8	14	18	22	17	23	17	18	11	5	3	4	2	4	0	1					
Darwin rain	61								1	1	4	2	3	4	4	12	8	6	5	5	2	1	1	2								
Fortaleza rain	72										4	5	7	1	7	12	11	7	7	4	1	2	1	1	2							
Frankfurt rain	71									1	2	1	3	12	10	9	13	2	4	5	3	3	1	1	1							
Greenwich rain	111						1	0	0	1	3	5	10	8	16	19	12	7	7	7	6	4	2	1	1	1						
Helsingfors rain	96								4	2	3	2	5	11	9	8	11	10	14	5	6	5	1									
Huron outflow	89									3	4	6	3	11	8	12	8	6	8	6	5	5	4									
Madras rain	100									3	1	6	5	14	13	14	9	9	8	5	4	3	3	2	1							
Milan rain	183						1	0	0	2	5	11	13	18	29	19	18	18	10	15	8	7	7	0	0	0	2					
New York rain	120									2	2	4	10	14	14	14	12	14	14	7	2	3	3	2	1	2						
Padua rain	171								1	3	6	7	13	18	20	22	18	19	15	8	7	7	4	1	0	1						
Philadelphia rain	126									3	6	1	11	7	17	14	10	18	16	10	6	1	2	2	1	0	1					
Portsmouth rain	98							2	1	0	3	5	7	8	8	13	17	8	7	10	4	1	1	2	1							
Rome rain	164						1	1	0	2	7	3	12	17	15	26	17	16	21	11	5	7	1	0	1	0	1	0	1			
St Louis rain	114									2	8	1	6	13	11	20	13	12	10	9	4	1	0	1	1	0	1	0	1			
St Paul rain	114					1	0		1	2	3	3	3	18	20	11	11	13	9	9	4	1	2	2	0	0	0	0	0	1		
Stockholm rain	161							0	2	2	2	12	16	15	16	15	17	15	13	15	6	8	5	1	0	1						
Sydney rain	111									2	2	6	7	15	19	15	12	5	9	4	6	3	2	1	1	2						
Trier rain	117						1	0	2	2	3	2	7	12	15	23	7	13	7	6	10	3	1	0	3							
Washington rain	111						1	0	4	0	2	3	6	15	10	13	16	13	9	7	3	4	1	2	2							
Roda gauge 641–740	99							2	1	3	1	2	3	8	8	16	15	15	11	7	2	3	1	0	1							
,, ,, 741–840	100						1	0	1	3	0	9	6	8	9	7	11	8	16	14	0	5	2									
,, ,, 841–940	100			1	0	0	0	1	2	2	1	2	7	8	11	7	6	14	16	19	3											
,, ,, 941–1041	100	1	0	0	0	0	1	0	0	0	1	4	4	5	15	18	14	15	11	9	0	0	2									
,, ,, 1042–1132	90		1	0	0	0	0	0	3	0	1	5	4	10	4	12	11	9	13	8	6	2	1									
,, ,, 1133–1255	122	1	0	0	0	1	0	0	2	1	0	6	5	11	12	17	15	17	12	13	9											
,, ,, 1256–1337	81						1	0	1	1	4	8	12	6	10	8	11	10	2	5	2											
,, ,, 1341–1448	107									1	3	11	9	7	7	8	14	18	6	13	5	4	0	0	0	0	0	0	0	0	0	1
Berlin temperature	173							4	1	5	3	2	14	16	9	21	28	14	20	19	7	5	3	2								
Charleston temperature	123									1	5	8	10	4	18	16	7	21	14	10	4	2	0	1	0	0	0	0	1	0	0	1
De Bilt temperature	211				1	0	1	2	2	3	7	10	13	13	19	19	42	25	15	16	10	9	1	3								
Greenwich temperature	105				1	0	0	1	1	2	3	3	8	6	13	16	10	7	13	7	7	3	2	1	0	1						
Helsingfors temperature	112							1	2	3	3	5	5	7	11	12	16	19	8	6	7	4	1	0	2							
Paris temperature	171								2	5	4	10	14	8	12	32	19	16	16	15	6	7	3	0	2							
Rome temperature	118							1	1	0	0	6	7	6	15	14	8	19	7	18	4	3	5	0	2	1	0	0	1			
St Louis temperature	115								1	1	4	5	12	9	12	13	12	13	11	10	4	2	2	2	2							
Stockholm temperature	178							1	2	1	10	7	9	20	17	27	16	13	20	14	9	6	3	0	3							
Vienna temperature	176							1	3	0	5	6	17	15	19	25	20	27	8	6	11	5	3	5								
Washington temperature	116								1	3	2	6	9	12	10	14	10	19	6	12	3	5	3	0	1							
Total	5916	2	1	1	2	2	9	19	48	79	157	266	425	537	648	753	701	635	518	448	251	178	108	53	41	16	7	3	4	1	0	2
Average	116																															
Parts per 1,000		0·34	0·17	0·17	0·34	0·34	1·52	3·12	8·1	13·3	26·5	44·9	71·8	90·8	109·5	127·4	118·6	107·4	87·6	75·8	42·4	30·1	18·3	9·0	6·9	2·70	1·18	0·51	0·68	0·17	0	0·34
Accumulated sums		0·3	0·5	0·7	1·0	1·4	2·9	6·0	14	27	54	99	171	266	371	498	617	724	812	888	930	960	978	988	994·4	997·1	998·3	998·8	999·5	999·6		1000

TABLE 3.—STATIONS AND DATA

Station and phenomenon	Period	Data for whole period				Data for first 30 years			Result of regulation 4
		Number of years : N	Mean : M	Standard deviation : σ	Index K	Mean : M_0	Standard deviation : $\sigma'=1{\cdot}1\sigma$	Computed capacity : R'_{100}	
Rainfall									
Adelaide, Australia	1839–1950	112	21	4·2	0·55	21·6	4·3	72	BD
Albany, U.S.A.	1826–1945	120	37	6·0	0·85	40·7	5·8	95	BC
Bangalore, India	1835–1946	112	35	7·7	0·50	35·5	8·1	135	BD
Boston, U.S.A.	1818–1945	128	42	7·0	0·83	41·6	7·4	123	AD
Calcutta, India	1829–1946	118	64	11·6	0·68	64·9	10·0	166	BD
Cape Town, S.Africa	1838–1949	112	24·5	5·2	0·73	23·7	4·8	80	AD
Charleston, U.S.A.	1832–1945	114	47	10·7	0·82	45·4	9·7	161	AD
Frankfurt, Germany	1837–1941	105	63	12·7	0·74	61·2	16·3	270	BD
Greenwich, U.K.	1841–1951	111	613	104	0·57	614	133	2210	BD
Helsinki, Finland	1845–1930	96	625	116	0·83	554	118	1960	AD
Madras, India	1813–1945	133	50	15·1	0·55	47·7	16·5	274	BD
Milan, Italy	1764–1936	171	100	19	0·71	92·7	17·7	294	AD
New York, U.S.A.	1826–1945	120	42	6·3	0·74	39·6	7·5	124	AD
Padua, Italy	1764–1934	171	848	178	0·73	926	228	3440	BD
Philadelphia, U.S.A.	1820–1945	126	42	6·3	0·76	42·4	6·8	113	AD
Portsmouth, U.S.A.	1830–1930	98	41	6·9	0·65	40·2	10·3	171	BD
Rome, Italy	1782–1945	164	83	16·8	0·72	82·5	16·3	271	BC
St Louis, U.S.A.	1838–1950	114	39	8·1	0·75	36·4	10·6	175	BD
St Paul, U.S.A.	1837–1950	114	27	5·6	0·73	23·9	7·2	120	BD
Stockholm, Sweden	1785–1946	162	49	12·3	0·91	55·4	13·8	230	BC
Trier, Germany	1806–1940	117	69	11·5	0·72	66·4	12·5	204	AD
Sydney, Australia	1840–1950	111	47	13·2	0·68	49·3	15·9	264	BD
Vanersborg, Sweden	1860–1944	85	72	12·6	0·69	72·7	14·4	240	BD
Washington, U.S.A.	1824–1950	111	41	7·9	0·71	38·1	9·6	159	BD
Zwanenberg (De Bilt) Netherlands	1735–1945	211	74	12·4	0·66	76·3	16·4	272	BC

A denotes reservoir fills.

B „ reservoir does not fill.

C denotes reservoir empties.

D „ reservoir does not empty.

Station and phenomenon	Period	Data for whole period				Data for first 30 years			Result of regulation 4
		Number of years : N	Mean : M	Standard deviation : σ	Index K	Mean M_0	Standard deviation : $\sigma'=1{\cdot}1\sigma$	Computed capacity R'_{100}	
Discharges and levels									
Nile, Aswan, Egypt (discharge)	1870–1949	80	93	18·4	0·90	109	16·1	268	BC
Dalalven Lake, Sweden (level)	1765–1940	176	192	30	0·75	218	35·3	587	BC
Lake Huron, U.S.A. (discharge)	1860–1948	89	188	20	0·94	211	9·6	160	BC
Roda gauge, Egypt (level)	641–740	100	9·0	0·72	0·68	9·1	0·51	8·4	BC
	741–840	100	8·7	0·61	0·65	8·8	0·59	9·9	BD
	841–940	100	8·8	0·51	0·74	8·7	0·47	7·9	BD
	941–1040	100	8·4	0·38	0·65	8·5	0·75	12·5	BD
	1036–1140	100	8·8	0·44	0·82	8·4	0·69	10·6	BD
	1136–1240	100	8·6	0·48	0·86	9·0	0·38	6·3	BC
	1241–1340	100	8·5	0·44	0·72	8·6	0·59	9·9	BD
	1341–1440	100	9·2	0·66	0·78	8·5	0·58	9·6	AD
Truckee River U.S.A. (discharge)	1839–1938	100	100	73	0·69	90·5	113	1880	BD
Varves									
Lake Saki, Russia	1490–1589	100	15·0	7·4	0·69	17·0	10·7	178	BD
	1590–1689	100	14·8	5·7	0·68	15·4	7·3	121	BD
	1690–1789	100	16·3	12·5	0·66	15·3	6·0	100	AD
	1790–1889	100	16·3	7·8	0·75	16·1	10·9	181	BD
Temperatures									
Berlin, Germany	1769–1941	173	9·0	0·88	0·74	9·1	0·96	15·9	BC
Charleston, U.S.A.	1823–1945	123	65·8	1·14	0·77	66·4	1·56	25·9	BD
Greenwich, U.K.	1841–1945	105	49·8	1·04	0·67	49·8	1·25	20·8	BD
Helsinki, Finland	1829–1940	112	4·39	1·10	0·78	4·62	0·90	15·0	AD
Paris, France	1764–1938	173	10·6	0·78	0·74	11·0	1·08	17·9	BD
Rome, Italy	1811–1930	119	15·3	0·54	0·79	15·6	0·73	12·1	BD
St Louis, U.S.A.	1836–1950	115	55·9	1·50	0·82	55·0	1·38	22·8	AD
Stockholm, Sweden	1764–1942	178	5·7	0·97	0·68	6·2	1·09	18·1	BD
Vienna, Austria	1825–1950	126	9·35	0·87	0·73	10·3	0·96	15·9	BD
Washington, U.S.A.	1820–1950	116	55·3	1·60	0·79	55·1	2·01	33·4	BD
Zwanenberg (De Bilt), Netherlands	1735–1945	211	9·0	0·72	0·66	9·1	0·85	14·1	BD

TABLE 4.—RESULTS OF REGULATIONS BASED ON INITIAL DATA FROM 30 YEARS

Subscripts denote length of period

Capacity $R'_{100} = 16{\cdot}7\sigma'$; $\sigma' = 1{\cdot}1\sigma_{30}$

Regulation	No. of phenomena	Starting content	Draft	Percentage of cases	
				Reservoir fills	Reservoir empties
Type (*a*)) 3	51	$\frac{1}{2}R'_{100}$	M_{30}	44	38
Type (*b*)) 4	51	$\frac{1}{2}R'_{100}$	M_{10} changing every 5 years	23	19
5	51	$\frac{3}{4}R'_{100}$	,, ,,	56	5
6	51	R'_{100}	,, ,,		2
7	51	$\frac{1}{2}R'_{100}$	M_{10} changing every year	12	15

raft, depending on the mean inflow during the period immediately preceding, essened the chances of emptying the reservoir. Of the cases where the reservoir started half-full the most satisfactory was regulation 7 with a draft equal to the mean upply of the previous 10 years.

In Table 5 the cases in which the reservoir emptied with regulation 4 are given and ne constant reduction to the draft which would have prevented emptying is included. Regulations 5, 6, and 7 with reduction of draft are also given.

TABLE 5.—DIFFICULT CASES

REDUCTION OF DRAFT REQUIRED TO PREVENT EMPTYING

NE means that the reservoir did not empty; $\sigma' = 1{\cdot}1\sigma_{30}$

Phenomenon	Reduction of draft to prevent emptying			
	Reg. 4	Reg. 5	Reg. 6	Reg. 7
Albany rainfall	$0{\cdot}06\sigma'$	NE	NE	$0{\cdot}03\sigma'$
Aswan discharge	$0{\cdot}43\sigma'$	$0{\cdot}10\sigma'$	NE	$0{\cdot}14\sigma'$
Berlin temperature	$0{\cdot}18\sigma'$	NE	NE	$0{\cdot}03\sigma'$
Dalalven lake levels	$0{\cdot}005\sigma'$	NE	NE	NE
Lake Huron outflow	$1{\cdot}4\sigma'$	$1{\cdot}0\sigma'$	$0{\cdot}62\sigma'$	$0{\cdot}9\sigma'$
Roda gauge 641–740 A.D.	$0{\cdot}31\sigma'$	$0{\cdot}12\sigma'$	NE	$0{\cdot}14\sigma'$
,, ,, 1141–1245 A.D.	$0{\cdot}03\sigma'$	NE	NE	Very small
Rome rainfall	$0{\cdot}04\sigma'$	NE	NE	NE
Stockholm rainfall	$0{\cdot}07\sigma'$	NE	NE	NE
Swanenberg rainfall	$0{\cdot}02\sigma'$	NE	NE	$0{\cdot}007\sigma'$
Calcutta rainfall	NE	NE	NE	NE
Roda gauge 841–940 A.D.	NE	NE	NE	$0{\cdot}058\sigma'$
Means	$0{\cdot}26\sigma'$			$0{\cdot}19\sigma'$

Regulation 7 is the better of the two which start with the reservoir half-full, and . reduction of draft of $0{\cdot}1\sigma$ would have prevented the reservoir emptying in all but .% of the cases. If it were permissible to start with the reservoir full, as in regulation ., a draft of M_{10} changing every year would have met all cases except that of Lake Huron outflow, i.e., all but 2%.

Type (c), regulation 8 was tried in one case, that of the Nile discharge at Aswan,

which was the second most difficult in Table 5. A drastic scale of reduction of draft with decreasing content was needed to prevent emptying, and it did not meet the case of a change of mean inflow so well as a draft varying with inflow. It was not thought a good enough scheme compared with others to be worth much labour to examine.

Type (d), regulation 9. The reservoir started half-full. The draft was M_{10} changing every year as in regulation 7, and further reduced or increased by a sliding scale in which the reservoir content was divided into nine parts. When the content is in the middle ninth the draft is M_{10}, if in the ninth below it is $M_{10} - g$, and so on down to $M_{10} - 4g$ where g is the step of the sliding scale. In Table 6 the value of the steps of the scales which would prevent the reservoir from emptying with regulation 7 have been calculated for six of the cases in Table 5. In the other cases a scale with a very small step would have been enough to have prevented emptying.

TABLE 6.—REGULATION 9. SLIDING SCALE APPLIED TO REGULATION 7
Size of step to prevent emptying
Starting content $\frac{1}{2}R_{100}$

Phenomenon	Step	Phenomenon	Step
Albany rainfall . . .	$0{\cdot}001\sigma'$	Lake Huron outflow . .	$0{\cdot}5\sigma'$
Aswan discharge . . .	$0{\cdot}5\sigma'$	Roda gauge 641–740 A.D. .	$0{\cdot}4\sigma'$
Berlin temperature . .	$0{\cdot}01\sigma'$	,, ,, 841–940 A.D. .	$0{\cdot}04\sigma'$

As a measure of safety against floods the scale could be applied to contents in the upper $\frac{4}{9}$ of the reservoir to increase the draft.

The result of regulation 9 is that in 14% of the cases a sliding scale would be needed to prevent emptying and in only about 10% would this have made more than a trifling reduction of draft on M_{10}. It looks as if regulation 9 is the type which would be most generally useful.

General remarks on the regulations

The type of regulation to fit any particular case depends upon its special conditions and probably no type will meet all conditions. The risk to be taken will of course depend on the greatness of the disaster which might occur in case of emptying and the cost of remedial measures, and these must be fixed by the circumstances of each case. The present investigation, however, enables the chance of failure of a particular regulation to be calculated.

It is evident from regulation 3 that the large changes which take place in the mean value, even when it is calculated from 50 years, make a fixed draft impracticable, unless the reservoir can start full and the draft is well below the mean. This involves also the condition that spilling is unimportant, which may be the case if only part of the flow is needed. To meet changes of mean the best device seems to be a draft varying with the inflow. The addition of a sliding scale depending on the content gives a further measure of safety against emptying and can be applied also in the case of flood protection. A 20-year mean changing every year was tried in the difficult case of Aswan discharge (see Fig. 5) but was not so satisfactory as a 10-year mean. It did not change rapidly enough to meet the considerable and abrupt change in discharge which occurred, and needed a large reduction in draft to avoid emptying the reservoir.

Analysis of difficult cases

There is difficulty in regulation when the mean, standard deviation or the index K (equation (1)) have different values after regulation has commenced from those in the previous period on which the content is based. Table 7 contains data relating to seven cases where such changes led to reduced drafts in order to prevent the reservoirs from emptying. Possible regulations are shown in Figs 4 to 11, in which the nature of the difficulties clearly appear.

For each phenomenon the mean, standard deviation and K are given in Table 7: (a) for the first 30 years, whose data are supposed to be known; (b) for the period during which the difficulties arise for the regulation; and (c) for the whole period of observations.

In every case the main cause of difficulty is that after regulation has started there is a pronounced reduction of the mean discharge which may extend over 50 years or more. In the case of Lake Huron discharge and Roda gauge the effect of this tends to be increased by an increase of standard deviation, and in the case of Lake Huron discharge also by a value of K much greater than the average adopted in calculating the reservoir capacity.

TABLE 7.—DATA RELATING TO DIFFICULT CASES OF REGULATION

	Date	Mean M	Standard deviation σ	K	Causes of difficulty
Lake Huron outflow: thousand of cu. ft/sec	1860–1889 1890–1948 1860–1948	211 177 188	8·7 12·6 20·0	0·83 0·87 0·94	Decrease of M Increase of σ High value of K (Figs 4a and 4b)
Nile, Aswan, annual discharge: milliards of cu. m	1870–1899 1900–1952 1870–1952	109 83 93	14·5 12·6 18·4	0·65 0·53 0·90	Decrease of M (Figs 5, 6a, and 6b)
Nile, Roda gauge: m	641–670 671–696 641–740	9·1 8·6 9·0	0·46 0·76 0·72	0·60 0·77 0·68	Decrease of M Increase of σ (Figs 7a and 7b)
Berlin temperature: °C	1769–1798 1799–1817 1769–1939	9·1 8·2 9·0	0·87 0·90 0·88	0·61 0·71 0·74	Decrease of M (Figs 8a and 8b)
Stockholm rain: cm	1785–1814 1815–1874 1785–1946	55·4 39·1 49	12·4 8·2 12·3	0·73 0·61 0·91	Decrease of M (Fig. 9)
Albany rainfall: in.	1826–1855 1891–1945 1826–1945	40·7 33·5 37	5·2 4·4 6·0	0·52 0·67 0·85	Decrease of M (Fig. 10)
Rome rainfall: cm	1783–1810 1826–1852 1783–1945	82·5 69·9 83	14·7 15·2 16·8	0·49 0·59 0·72	Decrease of M (Fig. 11)

Variations of draft

Since it is not possible to maintain a steady draft for long periods it is necessary to find out how the drafts vary for different regulations. The curves of accumulated

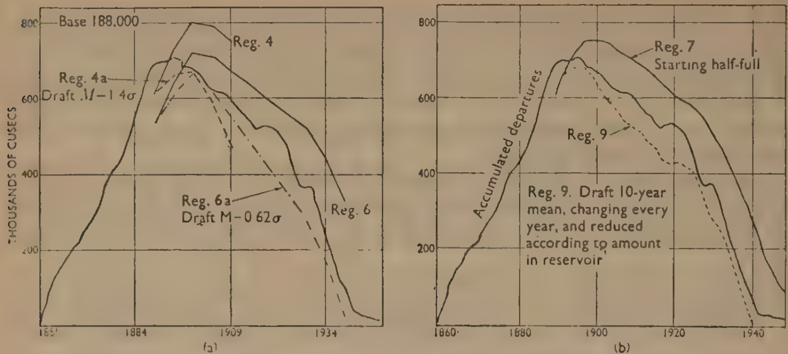

FIG. 4.—ACCUMULATED DEPARTURES. LAKE HURON OUTFLOW

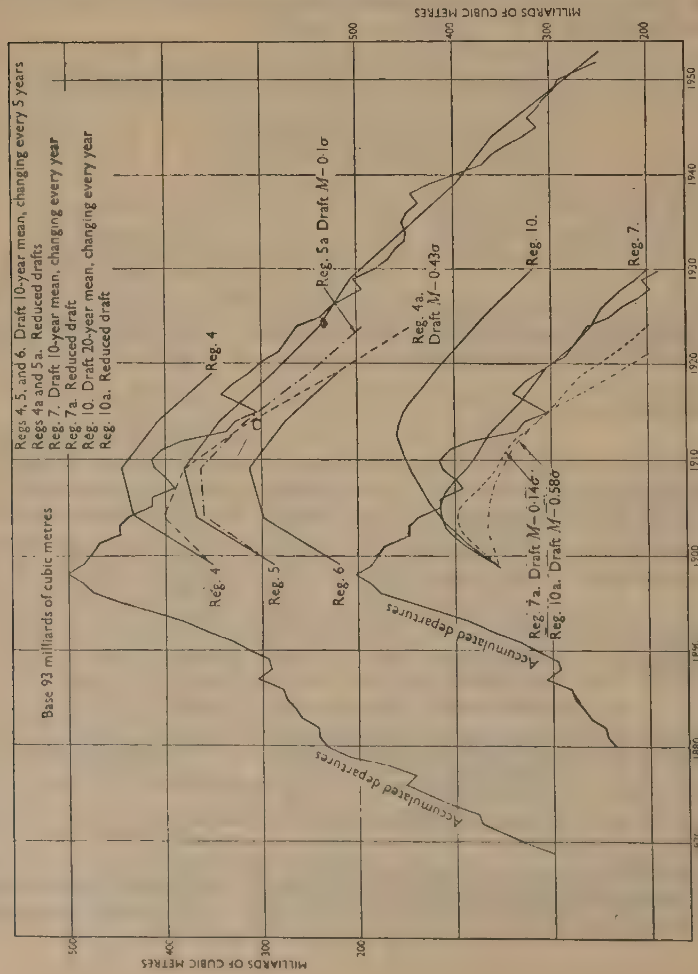

FIG. 5.—ASWAN DISCHARGE. ACCUMULATED DEPARTURES

departures with regulations 4, 5, and 6 enable this to be done for the phenomena examined. For each phenomenon the minimum 30-year mean, the minimum 10-year mean (using these at 5-year intervals), and the minimum mean less $0{\cdot}1\sigma$ have been tabulated. Now 30 years is a long period in the life of a farm or a hydro-electric

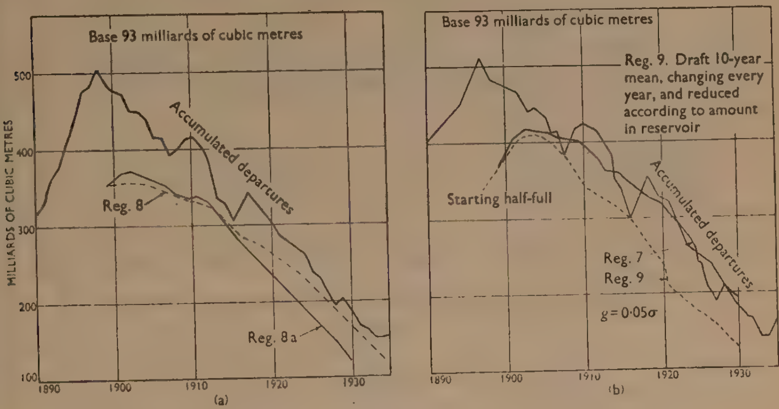

FIG. 6.—ACCUMULATED DEPARTURES. ASWAN DISCHARGE

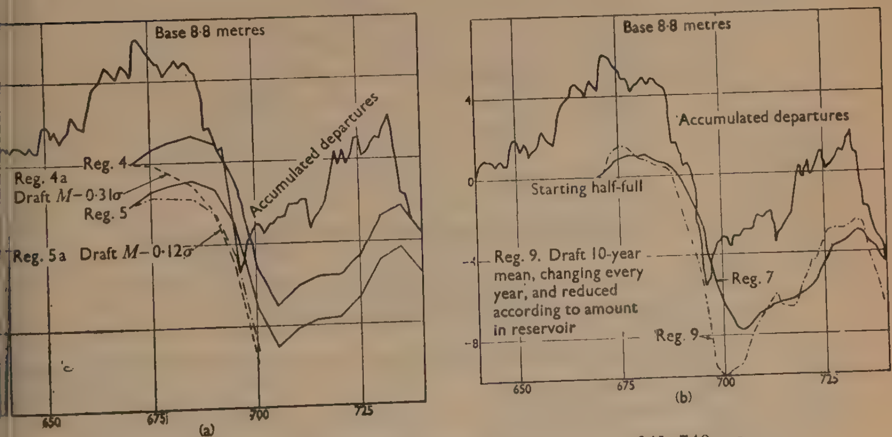

FIG. 7.—ACCUMULATED DEPARTURES. RODA GAUGE 641–740 A.D.

power scheme, and covers more than a generation, so it gives a useful standard of comparison.

	Mean value
(Lowest 10-year mean)/(Lowest 30-year mean)	0·95
(Lowest 10-year mean $-$ $0{\cdot}1\sigma$)/(Lowest 30-year mean)	0·93

Forty-six cases are included in the above means, from which four varves have been excluded since all gave values of the first ratio of about 0·80, which is lower than the

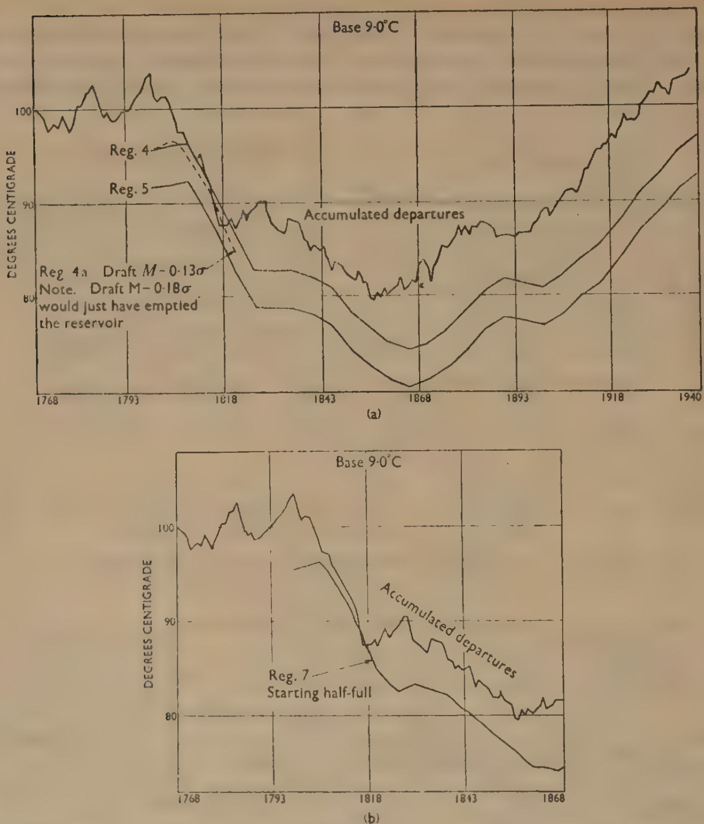

FIG. 8.—ACCUMULATED DEPARTURES. BERLIN TEMPERATURE

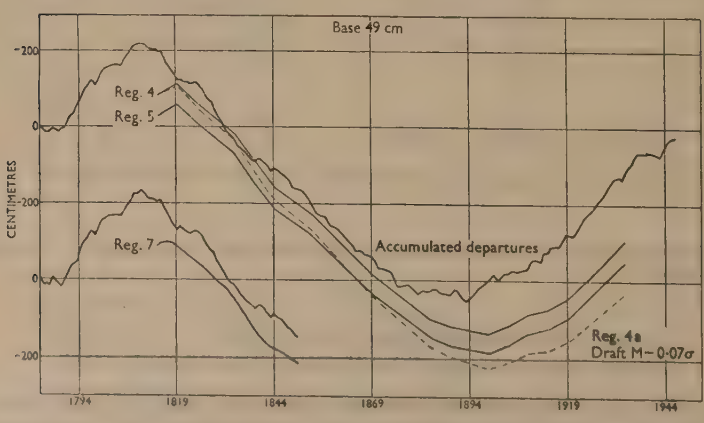

FIG. 9.—ACCUMULATED DEPARTURES. STOCKHOLM RAIN

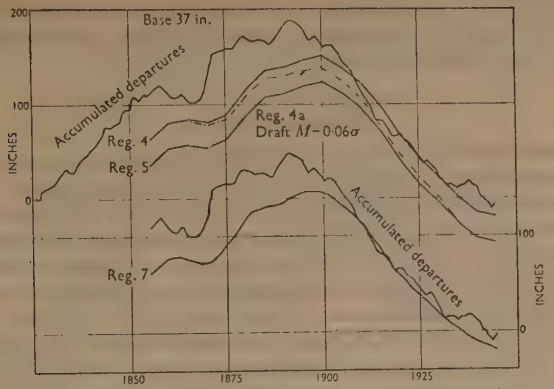

FIG. 10.—ACCUMULATED DEPARTURES. ALBANY RAINFALL

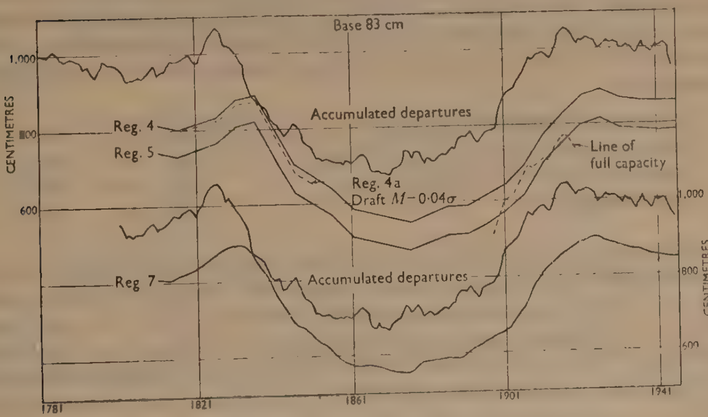

FIG. 11.—ACCUMULATED DEPARTURES. ROME RAINFALL

lowest value 0·84 found for the other forty-six phenomena. The frequencies of the ratios are:—

Range of ratio	1·0–0·96	0·95–0·91	0·90–0·86	0·86–0·81	0·80
	Percentage frequencies				
M_{10}/M_{30}	54	35	9	2	—
$(M_{10} - 0{\cdot}1\sigma)/M_{30}$ . .	35	46	13	4	2

Thus the lowest 10-year mean is not more than 9% lower than the lowest 30-year mean in 89% of the cases, and $(M_{10} - 0{\cdot}1\sigma)$ is not more than 9% less in 81% of the cases.

Nine per cent is easily within the tolerance of crops when the reservoir is used for irrigation and would cause no great hardship on a domestic water supply. In the

case of a hydro-electric power scheme the unavoidable variation of head, whatever the scheme, would probably be a greater factor in reducing the amount of firm power available than the reduction in draft.

Flood protection

In the previous sections the only consideration has been to make the best use of the available water without allowing the reservoir to remain empty. In some cases, however, another condition may be vital, namely, that the discharge out of the reservoir must not exceed a certain limit, otherwise the river below the reservoir will be in flood and there will be a danger to life and property. It is this condition which will now be examined. The limiting safe discharge in any particular case will, of course, depend on its special circumstances. So all that can be done here is to deal in a general statistical way with the fifty-one phenomena for which regulations have been calculated. The first attempt dealt with regulations 4 and 5, which had been worked out fully for all the phenomena. Three cases of total permissible annual discharges were considered, those which would occur on the average respectively, 1 year in 10, 1 year in 20, and 1 year in 50. Criteria for these were found from the main curve of Fig. 2. Dividing lines were fixed so as to separate the highest 10%, 5%, and 2% of the observations. The positions of these lines were defined by their departures from the mean expressed in terms of the standard deviations of the phenomena. Supposing a division to occur at a departure X from the mean the average values of X/σ were as follows:—

Values of X/σ separating highest . . .	10%	5%	2%
Values derived from the curve of Fig. 2 . .	1·3	1·7	2·15
Values from normal Gaussian curve . . .	1·28	1·65	2·06
Values adopted	1·3	1·7	2·1

The method adopted was to find in each of the cases of regulations 4 and 5 in which the reservoir filled to its defined capacity, what extra storage would be required to prevent the outflow exceeding the mean by more than $1{\cdot}3\sigma$, $1{\cdot}7\sigma$, and $2{\cdot}1\sigma$, corresponding to permissible high floods occurring on the average 1 in 10, 1 in 20, or 1 in 50 times. The graphic method of doing this is shown in Figs 12 to 14, and this is the easiest and probably the most reliable way, though care is needed to avoid mistakes.

Fig. 12 shows regulations 4 and 5 as applied to the accumulated-departures of Charleston rainfall. The ordinate between the line representing regulation 4 and the curve of accumulated departures is the amount of water in the reservoir at the corresponding date. The broken line is a duplicate of the accumulated-departures curve drawn below it at a fixed distance equal to the capacity of the reservoir when full. At the point where it crosses regulation 4 the reservoir is full and the whole discharge must be passed. The accumulated excess of the whole discharge over the amount required by the regulation is given by the maximum difference between the broken line and the regulation curve. This occurs in 1878. Fig. 13 shows on a larger scale part of the period of greatest excess over requirements. Lines a, b and c have been drawn to represent drafts such that 10%, 5%, or 2% of years would have greater discharges. We start with 1871 when with regulation 5 the reservoir would have been full. The three draft lines which have been drawn show that with drafts a, b, and c the reservoir would over-fill. It is now assumed that some capacity at present undefined, is available for flood protection above the normal capacity o

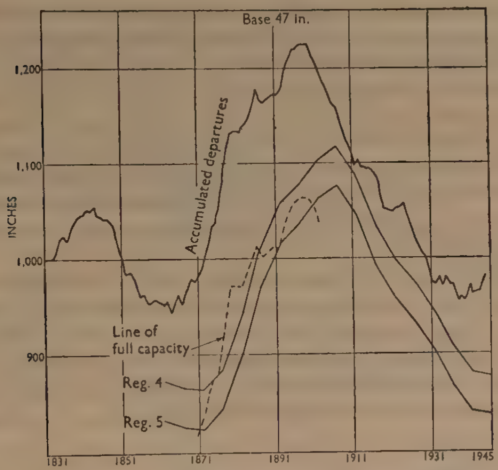

FIG. 12.—ACCUMULATED DEPARTURES. CHARLESTON RAINFALL

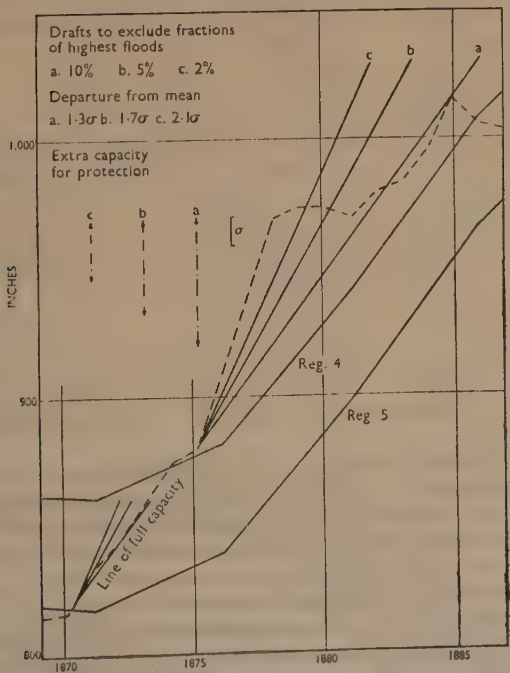

FIG. 13.—CHARLESTON RAIN. FLOOD PROTECTION

the reservoir (R_{100}) which has previously been calculated. The standard procedure for regulation would then be as follows.

When, following the standard regulation, the reservoir is full to its normal capacity it would be maintained at this level by allowing the draft to increase so as to dispose of the surplus. The draft, however, would not be allowed to increase beyond what had been decided as the permissible safe limit. When this was reached the flood-protection storage would come into use and the draft would be kept steady at the permissible limit. This would continue until the natural discharge fell below the permissible draft, which would be maintained until the reservoir fell to its normal full capacity. The reservoir would then be kept steady at the full level until the draft decreased to that appropriate to the standard regulation, after which regulation would proceed normally.

This procedure will now be followed in Fig. 13 for regulation 5. Normal full capacity is reached early in 1871 and the draft lines show that draft (a) would not keep the reservoir down to normal full capacity, but would entail the use of some extra storage. Drafts (b) or (c) would avoid this, and in fact with (c) the reservoir would fall below its normal high water mark. Continuing with draft (a) to the beginning of 1875 the reservoir would remain full or slightly over. In 1875 the net supply

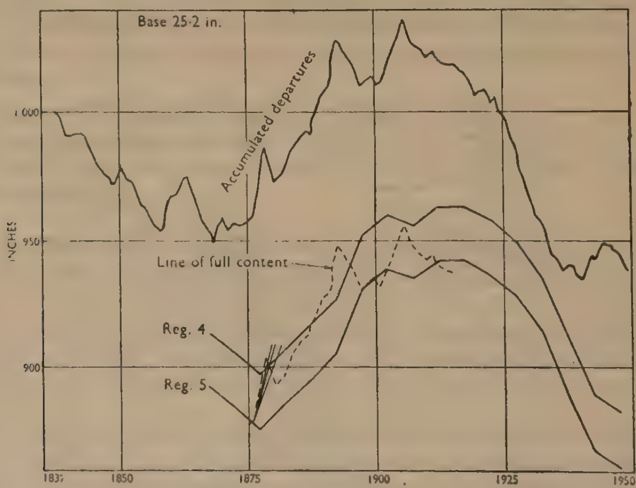

FIG. 14.—ACCUMULATED DEPARTURES. CAPE TOWN RAINFALL

to the reservoir fell to the draft required by the standard regulation and this would have kept the reservoir full. In 1876 the supply increased considerably and none of the drafts (a), (b), or (c) would have been enough to cope with it, as shown by the lines representing them, so flood storage would have come into use reaching a maximum in 1878. With permissible draft (a) the flood storage would have reached the maximum amount shown by the difference between the broken curve for normal full capacity and the draft line (a). This is indicated by the broken line (a) between arrows on the left. Similar broken lines show the extra capacity required with permissible drafts (b) and (c), corresponding to 5% and 2% floods. Maintaining draft (a), by 1883 the reservoir would have fallen to its normal high water mark.

keeping this level the draft would decrease, but would increase to the permissible amount during 1884 and 1885. After this the supply fell away, but rose again and extra flood storage would have been required by 1892 (Fig. 12). Fig. 14 shows the same procedure applied to Cape Town rainfall.

Table 8 shows the results of applying this method of computation to twenty-eight

TABLE 8.—FLOOD PROTECTION

Cases of reservoirs which filled with regulation 4 and regulation 5. Extra capacity in terms of standard deviation for whole period of observations required to protect against 10%, 5%, and 2% floods

Phenomenon	Regulation 4			Regulation 5		
	10%	5%	2%	10%	5%	2%
	Extra-capacity unit, σ					
Adelaide rain	Not filled (N.F.)			0·5	0	0
Boston rain	1·7	0·7	0·2	2·2	0·9	0·2
Calcutta rain		N.F.		0·5	0	0
Cape Town rain	1·2	0	0	3·0	2·1	1·3
Charleston rain	4·7	3·5	2·3	4·7	3·5	2·3
Frankfurt rain		N.F.		0·2	0	0
Greenwich temperature		N.F.		0	0	0
Helsingfors rain	0	0	0	0	0	0
,, temperature	2·7	0·9	0·3	3·2	1·1	0·4
Madras rain		N.F.		0	0	0
Milan rain	0·8	0·3	0	0·8	0·3	0
New York rain	0·2	0	0	2·2	1·0	0·6
Padua rain		N.F.		1·1	0	0
Philadelphia rain	0	0	0	1·6	0	0
Roda gauge 741–840		N.F.		0	0	0
,, ,, 841–940		N.F.		0	0	0
,, ,, 1341–1440	0	0	0	0	0	0
Rome rain		N.F.		0	0	0
Rome temperature		N.F.		0·4	0	0
St Louis temperature	1·2	0	0	0	0	0
St Paul rain		N.F.		0·4	0	0
Stockholm rain		N.F.		0·6	0	0
Stockholm temperature		N.F.		1·0	0	0
Trier rain	0·6	0·3	0	0	0	0
Vienna temperature		N.F.		0	0	0
Washington rain		N.F.		1·2	0·9	0·4
Washington temperature		N.F.		0·2	0	0
Zwanenberg temperature		N.F.		0	0	0
Total	13·1	5·7	2·8	23·8	9·8	5·2
$N = 28$. Means of all cases	0·47	0·20	0·10	0·85	0·35	0·19

phenomena. One phenomenon, 100 years of varves in Lake Saki, has been omitted because a deviation of $7\frac{1}{2}$ times the standard deviation was recorded. Such a deviation with a Gaussian distribution would occur on the average less frequently than once in 10^{11} years and must be attributed to something catastrophic, for which allowance could not possibly be made, or possibly to a mistake.

TABLE 9.—SUMMARY OF THE PRINCIPAL FACTS GIVEN IN TABLE 8

	Regulation 4	Regulation 5
Total number of phenomena . . .	51	51
Number of cases of filling normal capacity .	11	28

	Number needing flood storage		Average amount of flood storage*	
	Reg. 4	Reg. 5	Reg. 4	Reg. 5
10% floods . .	8	17	$1{\cdot}6\sigma$	$1{\cdot}4\sigma$
5% ,, . .	5	7	$1{\cdot}1\sigma$	$1{\cdot}4\sigma$
2% ,, . .	3	6	$0{\cdot}9\sigma$	$0{\cdot}9\sigma$

	Number of cases with extra storage exceeding			
	σ		2σ	
	Reg. 4	Reg. 5	Reg. 4	Reg. 5
10% floods . .	5	8	2	5
5% ,, . .	1	3	1	2
2% ,, . .	1	2	1	1

Average time covered by regulation 92 years
* Zero values of flood storage are not included

In the case of the remaining twenty-three phenomena to which regulations were applied the reservoir did not fill with either regulations 4 or 5.

The extreme case is Charleston rainfall where extra storage for a 5% flood is $3{\cdot}5\sigma$ and for a 2% flood $2{\cdot}3\sigma$ (see Figs 12 and 13).

The effect of the permissible draft on the amount of flood storage required is shown in Fig. 15. In one case the permissible draft is shown as the percentage of years which it would include, and the diagram is plotted on probability paper. In the second case the storage is plotted against the average departure of the permissible draft from the mean annual discharge, in terms of the standard deviation. In each case the mean storage for the three worst cases with regulations 4 and 5 has been plotted, and also the mean storage in all cases in which any storage was required (Table 10) by combining the means of regulations 4 and 5. The diagrams show how the amount of flood storage for the sample of phenomena dealt with in the Paper falls off as the permissible draft is increased.

The permissible draft which can be released without danger will vary with nearly every case and will be determined by the special circumstances. As an extreme case it might be that any flood above the average inundated low-lying country, that is to say that in about one year in two when the reservoir was nearly full, damage would be caused. In this case it might be cheaper to find some other means of protection than increasing the size of the reservoir. It seems likely that most of the cases in

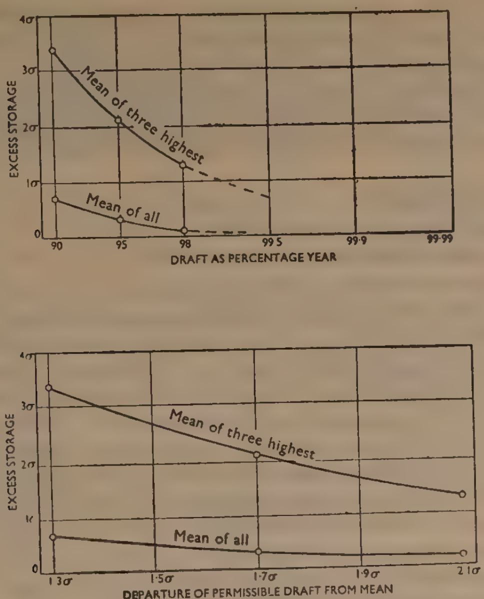

FIG. 15.—RELATION OF FLOOD STORAGE TO PERMISSIBLE DRAFT

practice would lie between a 95% and a 98% flood, and the limit defining the permissible draft would be between excesses above the mean discharge of $1{\cdot}7\sigma$ and $2{\cdot}1\sigma$. The factors by which the amount of flood storage to be provided will be determined will be discussed later.

The preceding discussion relates to regulations 4 and 5, which had been computed for all the phenomena, which however, later work showed are not those likely to be most generally useful. Considering all purposes regulation 9 is likely to be the one most commonly used (see p. 528). This will now be considered. The cases in which the reservoir emptied have already been discussed (pp. 527–28). Table 10 gives those cases in which the reservoir filled with regulation 7. It also gives the size of the step of a sliding scale depending on the content which is required in regulation 9 to prevent the reservoir from filling and spilling over.

Another example may here be given. It has been seen that the discharges at Aswan and out of Lake Huron provided two of the most difficult cases in regulating

TABLE 10.—REGULATION 9

SLIDING SCALES DEPENDING ON CONTENT APPLIED TO REGULATION 7

Phenomenon	Step
Cape Town rainfall	$0{\cdot}0067\sigma$
Charleston rainfall	$0{\cdot}165\sigma$
Helsingfors temperature . . .	$0{\cdot}067\sigma$
Roda gauge A.D. 1341–1440 . . .	$0{\cdot}040\sigma$
Trier rainfall	$0{\cdot}00025\sigma$

against drought. They are therefore likely to present difficult cases for flood regulation if their orders of occurrence are reversed. Whether a reversed order is a likely to occur as the original the Author is not prepared to say.

Regulation 7 has been applied to the two reversed cases and the total water in excess of the draft of regulation 7 after the reservoir is full (expressed in terms of the standard deviation assumed at the start of regulation) is given below:—

	Excess
Charleston rainfall	$4{\cdot}3\sigma$
Aswan discharge in reversed order . . .	$8{\cdot}0\sigma$
Lake Huron discharge in reversed order . . .	$8{\cdot}8\sigma$

The case of Charleston rainfall is given for comparison. In most cases not all this water would need to be stored since the maximum permissible draft would be greater than the maximum 10-year mean. Up to this point water could be spilt.

It is interesting to compare Tables 6 and 10. In one case the draft is regulated so that the reservoir just empties and does not remain empty, in the other so that it just fills and there is no necessity to spill excess water. It will be seen that the number of cases in both Tables is nearly the same, and also that the orders of magnitude of the steps of the sliding scales are similar. These characteristics no doubt arise from the fact that the frequency distributions of the phenomena are approximately symmetrical. It seems legitimate therefore to combine these and to say that a sliding scale with steps of $0{\cdot}2\sigma$, reducing the 10-year-mean draft at the smaller contents and increasing it at the larger contents would leave only four cases out of fifty-one in which the reservoir capacity would have been insufficient. In regulation 9 the greatest draft which has been used is the highest 10-year mean plus whatever increase may be produced by the application of the sliding scale. The highest 10-year means have therefore been tabulated for the phenomena under examination, together with their departures from the mean of the phenomena. These departures have been classified with their standard deviations as units. The greatest departure of a maximum 10-year mean from the mean of all observations of the phenomenon is $1{\cdot}87\sigma$, but this is not one of the cases where the reservoir fills. The average departure is $0{\cdot}91\sigma$. The smallest maximum 10-year mean cannot be less than the mean of all the observations, so $M_{10} - M$ has a lower limit of 0 and the frequency distribution of $(M_{10} - M)/\sigma$ is skew with the mode at about $0{\cdot}8\sigma$.

In the extreme cases given in Table 10 the reservoir is full at the time of the maximum 10-year mean, so the draft will be increased by the full effect of the sliding scale, i.e., $4g$. This is not necessarily the case but is the most usual occurrence and must be assumed in estimating the maximum draft according to regulation 9. Table 11 shows the details of the cases in the sample considered in which the content factor would be applied. M_{10} is the maximum 10-year mean, M the mean of all the observations, and σ the standard deviation of all the observations.

TABLE 11.—MAXIMUM DRAFTS IN TERMS OF σ WITH REGULATION 9

Phenomenon	$(M_{10} - M)/\sigma$	$4g/\sigma$	$(M_{10} - M + 4g)/\sigma$
Cape Town rainfall . . .	1·13	0·025	1·16
Charleston rainfall . . .	1·48	0·62	2·10
Trier rainfall	1·01	0·0009	1·01
Roda gauge 1341–1440 . .	0·24	0·12	0·36
Helsingfors temperature . .	1·46	0·22	1·68

For comparison it may be said that, if the frequency distribution is normal, a year with a discharge exceeding the mean by as much as or more than $2{\cdot}05\sigma$ occurs on the average once in fifty times, and by $2{\cdot}33\sigma$ once in 100 times (see Fig. 2).

As an example of regulation 9 the case of Charleston rainfall has been plotted with a sliding scale where $g = 1{\cdot}6$ or $0{\cdot}165\sigma$, and this is shown in Fig. 16. Regulation 7

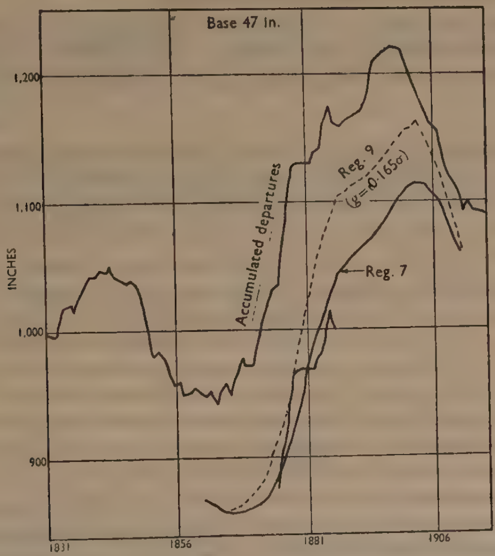

FIG. 16.—ACCUMULATED DEPARTURES. CHARLESTON RAINFALL

is also shown and, as in Fig. 12, the curve of accumulated totals is duplicated at a distance R'_{100} below the original so as to indicate the full capacity and the excess to be spilt with regulation 7, and to show that the reservoir just fills with regulation 9. The maximum draft which is given in Table 11 is $2{\cdot}1\sigma$ above the mean of the observations for the whole period of 114 years. This corresponds to the discharge in a year which would occur on the average about once in 50 years, and would not be an unreasonable value under some conditions for a maximum permissible draft, so that there should be no damage in high years. Charleston rainfall was very unusual in as much as the three highest years (which were in the 1870s) occurred in succession and had departures from the mean of $2{\cdot}9\sigma$, $2{\cdot}9\sigma$, and $2{\cdot}8\sigma$. Charleston is the only station of the fifty-one examined with three departures larger than $2{\cdot}7\sigma$; Albany is the only other station where two departures larger than $2{\cdot}7\sigma$ occurred, and they did so in successive years.

With natural phenomena, where there is a tendency for high or low values to be grouped together, the probability of high values occurring in successive years is greater than with random distributions. To the Author's knowledge the effect of grouping has not been investigated and the statistical work involved in estimating it would probably be heavy. In the frequency investigation on which Fig. 2 is based there are fifty-one samples of an average length of 116 years, the effect of grouping, or in other words variation of the mean, comes in to some extent. Where, however,

a sample covers only 40 or 50 years the mean and standard deviation are liable to larger errors than would be the case with a sample in which the order of occurrence was random. In the present Paper the use of a 10-year mean continually varying to some extent counteracts the effect on the mean of grouping. The variability of the standard deviation is probably not sufficiently compensated by increasing the value obtained from 30 years of observations by 10%. However, its effect will appear in the results of the regulations which have been tried.

It will be realized that many modifications in the details of the regulations which have been examined in this Paper are possible. Any modification, however, must be given a statistical test on the lines already explained before it can be safely tried in practice.

Factors which determine the amount of storage required for flood protection

This is clearly a more complicated problem than protection in the case of annual storage reservoirs which are filled in flood time and emptied during the following low stage. In the case of annual storage it is the volume of the maximum flood and the maximum safe discharge which are the determining factors. In the case of a long-term storage reservoir previous history has to be considered, and the final determining factor may not be the single maximum year but a succession of high years preceding. Also, on the one hand these critical years may occur when the reservoir is full, or on the other hand when nearly empty. In one case the extra capacity of flood protection will be needed, and in the other case not. In the case of Charleston rainfall (see Fig. 16), from 1843 until 1863 the rainfall was almost continuously below the average. Regulation started in 1861 and almost immediately the rainfall above the average occurred and was maintained almost continuously for 35 years. With regulation 7 by the end of 1875 the reservoir was within a very small distance of its top and the next year, the first of the three highest, overfilled it. In this case it might be said that the previous history was very largely responsible for overfilling, but the three successive high years were responsible for the amount of overfilling.

CONCLUSION

In this Paper and its predecessor the general theory underlying long-term storage problems have been given. Each problem, however, must be treated separately using as data the practical conditions by which it is governed. Nevertheless the records of the phenomenon which is to be regulated are not themselves sufficient to give a solution. This must also be based, as has been shown, on data relating to similar phenomena. About fifty cases have been analysed but valuable work could be done in extending this work to many more cases of phenomena whose frequency distributions are approximately Gaussian. Regulation 9, which bases draft on a variable mean together with a factor depending on the actual content of the reservoir, is undoubtedly the most successful of those which were examined. In extending the work to other phenomena, therefore, it would probably only be necessary to compute regulation 9.

Finally it is to be remembered that, as in most civil engineering questions, the data are not certainties for the future, but only probabilities of varying degrees. They must therefore be dealt with by the recognized methods of statistics and the factors of safety deducible from these must be applied.

The greater use of water as development goes on will produce more and more cases of long-term storage. One which has been studied, but still awaits a definite solution

agreed upon by the interested countries, is the working of the Equatorial Nile project, of which the first component, the Lake Victoria Reservoir, has been constructed, to which later must be added the Lake Kioga Regulator, the Lake Albert Reservoir, and the Jonglei Diversion Canal project. These involve protection against both drought and flood, and are more complicated than the cases considered in the present Paper.

ACKNOWLEDGEMENTS

Throughout the work described in this Paper, which has extended over several years, the Author has had valuable advice and assistance from his colleagues in the Egyptian Ministry of Public Works: Mr R. P. Black, M.C., M.A., B.Sc., now scientific Consultant, Ministry of Public Works; and Mr Yusef Simaika, B.Sc., Inspector-General, Nile Control, later Under-Secretary of State, and now Technical Consultant.

Mr Naguib Boulos, the Author's personal assistant for more than 30 years, has done a great deal of work on the details of the Paper, assisted by the staff of Nile Control. To all of these the Author offers his thanks.

The Paper, which was received on 17 June, 1955, is accompanied by twenty sheets of diagrams, from which the Figures in the text have been prepared.

Discussion

Mr W. N. Allan (Irrigation Consultant to the Sudan Government) said it was a notable achievement to have developed statistical equations in forms which fitted such varied types of phenomena, so that the consideration of a single case could be based on knowledge of the characteristics of a much larger sample. The Author had pointed out, in the conclusion, that each individual case must be treated separately, using as data the practical conditions by which it was governed. It was on that aspect of the subject, the practical consideration of individual cases, that Mr Allan commented, with particular reference to the effects and implications of the losses which in varying degrees were necessarily incurred in long-term storage.

In the Author's statistical investigations such losses had been ignored, for reasons which were obvious. There was no absolute relation between a phenomenon itself and the losses, which would vary with the conditions of storage and the methods of regulation adopted. But in the practical consideration of any individual case, the losses could not be disregarded, since they affected the amount of storage capacity which was hydrologically desirable, the net usable draft which could be maintained, and the methods of regulation which were most likely to be suitable.

To illustrate those points Mr Allan used the example of Aswan, not only because that was one of the cases which the Author had found to be difficult in regulation, but also because the rate of evaporation was high, and the losses were thus significant in relation to the total annual flows, so that their effects showed up clearly. For that site as a reservoir data were already available up to a capacity of about 130 milliards of cubic metres; from those Mr Allan had prepared a Table of annual losses extended to cover a much larger range, on the assumption, which seemed not unreasonable for preliminary purposes, that surface areas, and thus evaporation losses, would be in proportion to the contents to the power of two-thirds.

First, with regard to R, the range of accumulated departures from the mean, Fig. 6 showed that over the 80 years from 1870 to 1949 at Aswan the accumulated departures of the unaffected natural flows reached a maximum of 501 milliards in 1898. If there had

been no losses, that capacity would have just sufficed to maintain the average flow of 93 milliards throughout the period. But if in each successive year allowance was made for losses corresponding to the mean contents during that year, the maximum range would have been only about 375 milliards. A net usable draft of about 83 milliards could have been maintained, while the losses would have averaged slightly more than 10 milliards, the figures for individual years ranging up to 21 milliards. Thus in that particular case, taking account of the losses reduced the maximum accumulated departure by about 25%. Putting it in another way, the variable might be regarded not as the unaffected natural flow but as that flow less the losses involved. For the 80-year period Mr Allan found that the latter quantity had a standard deviation of about 16·1, compared with 18·4 for the standard deviation of the unaffected natural flows, as given in Table 3.

That was only one case, and perhaps a rather extreme one, but it illustrated clearly the nature of the effects caused by the losses. It appeared, therefore, that the investigation of any individual case for the capacity of reservoir hydrologically desirable, whilst giving due consideration to the guidance obtainable from the Author's results over a wide field, as embodied in equations (1) and (2), and to the various points which the Author had mentioned, notably the uncertainty as to the trends of future flows, must also take fully into account that factor of losses. It was true that in many instances the capacity to be provided would be decided on grounds other than those of hydrology only, e.g., for reasons of practicability, cost, and so on. But that should not affect the hydrological investigation itself.

With regard to methods of regulation, the Paper provided a lucid analysis of the results of different types, applied to the various classes of phenomena. Mr Allan agreed with the Author's remark that the choice of methods would depend on the special conditions of each case (he would add, particularly on the capacity provided), and that no one type of regulation was likely to be generally suitable. Subject to those remarks, Mr Allan's experience supported the Author's expectation that regulations on the lines of his type 9, if not his type 7, were most likely to prove suitable. But again, in estimating the chance of failure of any particular regulation applied to any particular capacity, the losses must be taken into account, since they really reduced the variable which was being considered. As yet Mr Allan could not suggest any better way of investigating that point than the rather crude and laborious one of working out various regulations and comparing their results. He hoped that the Author could suggest some means of improving on that.

Another point was that once the capacity of any long-term reservoir had been fixed, the adoption of methods of regulation which tended to keep the contents in the upper part of their range, whilst it decreased the risk of the reservoir emptying, at the same time increased the losses and so reduced the net usable draft. Using Aswan again as an example, and assuming, as in the Paper, a capacity of R'_{100}, which came to 268 milliards, Mr Allan had tried the effects of the Author's type 7 regulation, starting with different opening contents. Regulation 7 took as the draft each year the 10-year mean, M_{10}, changing every year; from that had to be deducted the loss appropriate to the contents. Starting with the reservoir half-full, i.e., contents 134 milliards, over the period of 80 years Mr Allan found that the reservoir neither filled nor emptied; the losses averaged about 11 milliards and the net usable draft varied from 98 to 72 milliards, with a mean of just under 83 milliards. Starting with a lower content, 80 milliards, the reservoir just emptied; the losses averaged just over 7 milliards and the net usable draft ranged from 101 to 76 milliards, with a mean of rather less than 87 milliards. In other words, in the second case the minimum net usable draft, and the mean, were greater than in the first case by nearly 4 milliards.

Again it was true that that was only one instance, but taking the losses into account would always show up that trend, and it appeared that in any case where the rates of loss were significant, methods and policies of regulation should be considered from that aspect. It was really a question of comparing the risk of the reservoir emptying with the certainty that if the methods of regulation were such as to use the higher part of the range of capacity provided, i.e., to keep the reservoir fuller as an over-riding policy, then the

net available water would be reduced. The difficulty of exceptionally low years could be met by having a special reserve of water, preferably located at some other site where the rates of evaporation loss were less serious. Such an arrangement might be possible in some cases, but not in others.

Mr Allan had not been able to examine in any actual instances the effects of losses on the question of storage for protection against floods. But in so far as losses reduced the contents of a reservoir they decreased the risk of its filling completely and so making it necessary to pass on the whole inflow as and when it arrived. In that respect too their effects had to be considered.

Further consideration showed even more clearly how capacity and methods of regulation reacted on each other, and must be considered together. For example, if in the case instanced above, the reservoir capacity was taken at 80 milliards only, instead of the large figure of 268 milliards assumed in line with the Paper, and if the normal net draft were based as before on the 10-year means less losses, but in that case not exceeding 83 milliards except when spilling was necessary, an interesting comparison could be made. In most of the first 30 years of the period, when the river flows were relatively large, the reservoir was full and considerable spilling occurred. But from 1901 to 1950, when lower flows predominated, the regulation was very nearly the same as with the second condition described above; again the reservoir just emptied, whilst the average net draft was nearly 81 milliards, as compared with about 82, and the minimum in any year, 76 milliards, was the same. It was remarkable that over the 44 years from 1907 to 1950, the reservoir of 80 milliards provided almost exactly the same usable amounts, year by year, as that of 268 milliards would have done. That illustrated the point that beyond a certain limit increases in capacity provided quite incommensurate increases in benefits, particularly in the amounts assured in low periods, which afforded the most important criteria. The determination of the optimum capacity in any individual case must be based on the actual data available for that case, with due regard also to the results of analysis over a wide field of different phenomena.

Mr J. K. Hunter (Consultant, Sir Alexander Gibb & Partners, Consulting Engineers) observed that there were three points which emerged from the Paper which had particularly impressed him. One was that there was no such thing as a fixed true average for the kind of natural phenomena, including river flow, which the Author had examined; the second was the way in which the observed values of all phenomena followed closely the normal Gaussian distribution; and, thirdly, in using the result of a finite series of river-flow observations for reservoir regulation it was not possible to be certain that in the future a fixed draft could be met unless that draft was set well below the observed mean.

With regard to the first point, Mr Hunter recalled that he had suggested previously that the widely held belief that the true mean flow of a river could be reliably determined by examining a 35-year record was not well founded in fact, and that such expressions as "average annual run-off" had no precise meaning except in relation to the particular records from which they had been derived. As an example, the annual flow of the River Thames for the past 71 years had been 2,674 cusecs; but if from those 71 years of records the 30 years from 1883 to 1912 and the 32 years from 1910 to 1941 were selected, average values equal to 88% and 116% of the 71-year average would be obtained.

So far as reservoir storage problems were concerned, it was now generally recognized that estimates of uniform draft based on a study of finite records were no more than approximations, and that longer records inevitably showed that a reduction in the estimated draft would at times be necessary if the reservoir were not to be emptied. Whilst it was not possible to estimate with certainty the uniform draft which could be sustained by a reservoir, it was nevertheless possible to obtain a useful guide to the percentage of the time for which a particular draft could be depended upon. That was valuable because it afforded an idea of the risk of a short fall occurring, so that the consequences could be evaluated in relation to the cost of reducing the risk by using a larger reservoir.

The statistical approach used by the Author for dealing with annual river flows and reservoir storage was, of course, equally applicable to flood discharge. In the past it had been common practice to estimate the maximum floods to be expected by using an empirical formula based on observations relating the flood to the size of the catchment area. Such formulae had no general validity outside the particular river system from which they had been derived, and they paid no heed to the probability aspect of such natural phenomena; they gave no indication of whether the flood had a chance of 1 in 10 of occurring in any particular year or a chance of 1 in 1,000. Since the formulae had been derived from observations of river systems of widely different characteristics, the results which they gave covered a correspondingly wide range. Mr Hunter showed a slide giving a selection of such formulae; according to the particular formula chosen the maximum flood from the catchment area, whether it were 1 sq. mile or 1,000, might vary over a range of 14 to 1. That demonstrated the uselessness of applying an empirical formula except in circumstances which it was known to fit.

In 1933 the Institution Committee on Floods had published their interim report,[3] which contained an enveloping curve based upon floods recorded in Great Britain. That curve gave what the Committee described as the normal maximum flood which might be expected from a catchment area of any size in Britain. Because of the acknowledged paucity of the data available at that time the Committee qualified their conclusions by pointing out that even higher floods might occur, and said that where particularly important or vulnerable dams were concerned it might be prudent to assume the possibility of a flood of twice the magnitude given by that curve. Since the publication of that report several instances had occurred in Britain of floods considerably in excess of the Committee's normal maximum flood, and the question arose as to the safety of those dams for which the spillways had been designed to accommodate such floods, and of the chances of the occurrence of a flood of perhaps two or three times the so-called maximum?

The only way to answer such a question seemed to be by applying the kind of analysis used by the Author in his study of the Nile, because there was no other way of peering into the future than by looking back into the past.

In conclusion, Mr Hunter pointed out that the engineer's interest in rivers lay in the use which they were, or could be, to mankind. The needs were always changing and it was never possible to achieve anything approaching a permanent balance between supply and demand. The essentially approximate character of all river calculations was thus of less importance than a knowledge of the variations which might occur. If those could be reliably assessed, the engineer was then in a position to estimate the risks of deficiencies arising and to adjust the demand to bring those risks within acceptable limits.

Mr C. G. Hawes (Consultant to the Government of Uganda and to the Uganda Electricity Board) observed that he had been dealing during the past 5 or 6 years with the Egyptian proposals for developments on the Nile, and during the past year he had done a good deal of work on the problems of regulating the lakes in East Africa in order to find out, first, how much water could be taken from them and, secondly, the effect of the regulations on the levels in the various lakes. The three lakes concerned were Lake Victoria, which was about 200 miles in diameter and which was now controlled by the Owen Falls scheme; then, 360 ft lower in level, Lake Kioga; and about 1,200 ft below that Lake Albert.

They had been working on a proposal to give a constant discharge either from Lake Albert using the waters available or further down the river at Mongalla, so that the torrents which joined the river between Lake Albert and Mongalla would be taken into account. One of the difficulties of the scheme had been that all those investigations must be based on past data. They had 54 years' data for Lake Victoria, 42 for Lake Albert, and a little less for Lake Kioga. Data of discharges from the lakes and also of the movement of the levels, had been available, so that it had been possible to isolate the effect

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[3] References 3 *et seq.* are given on p. 576.

of the lakes themselves month by month; that enabled them to change the system of regulation of one lake and observe its effect on the others.

The problem was how much provision had to be made for the future, and it was there that the Paper would help. The Author's conclusion that the standard deviation increased with the length of the period which was being considered would enable them to say that if they wanted to consider a 100–year period the standard deviation must be increased by the amount that the Author had given. By doing so a new outflow could be fixed from the main lake, Lake Victoria, and the effect of that determined all the way down the river, both on discharges which had to be passed and on levels which would be experienced.

In making those regulations, Mr Hawes considered that they must work not only with the measured discharges but also with the recorded levels, and that allowance for abnormal conditions to be met in future would have to be made. The Paper provided a logical basis for making those allowances. In the past the tendency had been to say "Let us start with a level of so much," because it was not known what would happen, and test regulations had been started with a reservoir half-full. Some of the regulations which Mr Hawes had done on the lakes had indicated that, using the natural levels of the lakes for existing regulations, it would be necessary to use up as much as 1 year's mean discharge from the system to bring one lake—in the case in question, Lake Albert—to the required level for control. That water was consequently not available for use down the Nile.

Mr E. Gold (formerly Deputy Director, Meteorological Office) thought that perhaps the outstanding feature of the Paper was the Author's emphasis on the value of frequencies, not in derogation of the average but as an essential supplement to the information about averages. Many years ago averages had been worshipped unduly, but there had been a reaction and now they might almost be regarded as in danger of unconsidered abolition. However, the average was a better guide to the future than pulling numbers at random out of a hat.

The Author's curves might give the impression that the distribution was the same as a random distribution, and he almost seemed to prove that that was so, but then he proved that it was not. It showed how when dealing with broad features broad conclusions were obtained, and then, when applying them to actual facts, it was necessary to go beyond the broad features to consider their differences. That was well brought out in some figures for rainfall which Mr Gold had worked out 26 years ago. The number of isolated dry and wet days which might be expected in a period of 10 years with random distribution was about 900; but if the records were examined it would be found that the isolated days—i.e., a wet day between 2 dry days, or a dry day between 2 wet days—instead of being 900 were only 600, which was a very big departure from the random position. Those figures illustrated as well as, and perhaps even better than, standard deviations the magnitude of the departure from the random distribution.

Mr Gold suggested that the Author should work out the persistence factor for some of the data with which he was concerned. The persistence factor was a measure of something to which the Author had drawn attention, that, with actual events, sequences or runs occurred more frequently than with random distribution. That effect could be measured by what was called the persistence factor. The persistence factor, for example, in the rainfall at Kew Observatory was 1·30. It was possible to represent it by:

$$\frac{1-p}{1-p_1}$$

if p was the probability of the occurrence of, for example, a rain-day and p_1 the probability that a rain-day would be followed by another rain-day, which was not the same as p. The persistence factor at Kew as measured by that formula came out as 1·30. The value of p for a wet day was 0·472 and of p_1 (the chance of a wet day being followed by another wet day) was 0·595. That could be borne in mind when considering forecasts.

The Author had shown a slide giving two formulae, the first of which was $R = 1{\cdot}25\sigma\sqrt{N}$

and the other $\log \frac{R}{\sigma} = K \log \frac{N}{2}$. The Author might not agree, since the σ was not strictly the same in the two formulae, but Mr Gold thought that it would be of interest to see what values would be obtained if (as could be done quite easily) R/σ was eliminated. That would give the equation $K \log \frac{N}{2} = \log 1{\cdot}25 + \frac{1}{2} \log N$. It was possible to find K from that if N was known. If N was 10,000 years then K was 0·57. If $N = 1{,}000$, then $K = 0{\cdot}59$; if $N = 200$, $K = 0{\cdot}62$; if $N = 100$, $K = 0{\cdot}65$. That was getting near to the Author's value. If $N = 30$, $K = 0{\cdot}71$, which was very close to the Author's value. It looked as if with a period of only 30 years there would be a random distribution. Mr Gold did not believe it, but those were the figures. With a period of only 10 years (the Author had given the warning not to take a small number!) $K = 0{\cdot}86$, and for $6\frac{1}{2}$ years $K = 1{\cdot}00$.

The Author's value was obtained at a period of about 30 years, and that had led Mr Gold to consider a rather peculiar aspect of Table 7. The numbers given there seemed to go in the wrong way, in that K became less as the period of years became longer, whereas, according to the Author's view that there was a bigger variation with increase in the number of years, it might be expected that K would get bigger with an increase in the number of years. In Table 7, however, taking Berlin, for a period of 18 years K was shown as 0·71, whereas for a period of 30 years it was 0·61. That went in the same direction as Mr Gold's figures, but was the wrong way according to the Author's general conclusions. In the case of Stockholm, for 30 years $K = 0{\cdot}73$, whereas for 60 years $K = 0{\cdot}61$.

The Author's comments on those points would be of interest, and Mr Gold suggested that the Author should work out the persistence factor for some of the data with which he was concerned and which were of more direct interest to water engineers than just the one for rainfall, which was 1·30.

Mr N. A. F. Rowntree (Partner, Messrs Rofe and Raffety, Consulting Engineers) remarked that he was particularly interested in the fluctuations of the statistical character of the data in time. The Author referred to the groupings of high and low values, with no obvious regularity. Was there any indication of a number of cyclic variations causing irregularity. It seemed to indicate that the data were not homogeneous and that they should be treated statistically with some trepidation; nevertheless the use of statistical methods was probably the only way to examine the records, but some caution was necessary.

A similar phenomenon of change of average was to be found in the 100-year records of the Chilgrove well.[4] Mr Rowntree had attempted some statistical work on that record, but he had found that the value of the results from a prediction point of view was greatly reduced owing to the variation of the mean, even over that comparatively short time. Such fluctuations in the mean and standard deviations led one to agree with the Author's conclusion that the methods of regulation described as Nos 7 and 9 were the correct ones for the circumstances. They were correct in the sense that they took note of the variations in mean values which were occurring and adjusted the methods of regulation accordingly. That did not mean, however, that it was possible to ignore the effects of the variations on the discharges which could be maintained.

That led Mr Rowntree to a particularly interesting point—in Britain there were now available in some cases 30 to 50 years of fairly good run-off records. Water engineers were occasionally surprised that their impounding reservoirs did not give as much water as expected. That might arise partly from a change in the statistical character of the run-off data. There were two ways in which extended information could effect such a change. The mere fact of having more data and longer-term data would allow new values to be assumed, but the additional factor of periodic changes in statistical nature was a newer conception and very important.

In Fig. 2 the probability curves showed excellent straight lines with upward and down-

ward deflexions at the higher and lower extremities. The Author's explanation of the deflexions was that in considering extreme values, such as the extreme values in a 100-year record, there was no reason why one or two of those extreme values should not be those which could be expected in, perhaps, 500 years and not just 100 years, so that in an investigation of that nature there were almost certain to be a few points at the end of the curves deviating from the straight line. For that reason it would be better to show that part of the curve as a broken line, or even to leave it out altogether.

Mr Rowntree assumed that the annual periods on which the data had been prepared were either calendar years or water years. A restricted conception of that sort could miss more extreme 12-month periods lying between those two, particularly in Britain; it might not be so applicable on the Nile. Had the Author considered the use of monthly moving averages of annual values either in the calculations (which might lead to some difficulties) or in determining which set of 12 months to take?

The Author's methods were likely to be of value in studying the dual-purpose use of reservoirs in Britain when sufficient run-off data became available.

Mr R. W. S. Thompson (Engineer to the Derwent Valley Water Board) said he suspected that the Author's discoveries had not come out exactly as he thought they would when he started. The facts of nature were extremely complicated, and many scientific investigators and explorers had set out to find one thing and found something slightly different.

The Author had suggested that the results of his researches could be applied to quite different circumstances all over the world. The Paper was the statistical treatment of a problem—everything was expressed in terms of the standard deviation, and by implication in terms of the coefficient of variation. The Author did not deal with the actual variants. Moreover, data relating to all sorts of phenomena were treated as though they were river discharges. That seemed to be a startling procedure, but the Author had convinced Mr Thompson that those other phenomena, such as temperatures and pressures, were comparable if the right statistical treatment was used. However, Mr Thompson still had a little doubt about the inclusion of the thickness of tree rings. The figures seemed to show that they fitted in like the others, but tree rings could vary in thickness a great deal according to the proximity of other trees and not entirely according to the variations of climate, to which the similarity of the other phenomena could be attributed. But the Author, in making his trial regulations, had not used tree-ring figures.

The opening sentence of the Paper gave the impression that the Author had an explicit formula, but on reading further and studying formula (1) it would be realized that that gave the storage which was the most likely to be the amount required. It was like a statistical average. There might be cases which required more and cases which required less. That was admitted by the Author, whose trials of different regulations were an acknowledgement of it. He finally showed how that difficulty could be overcome, but he took as the starting point throughout that the storage should be 16·7 times the standard deviation. He arrived at regulation 9, which seemed to be an admirable way of meeting the unknown variation of the mean, and the unknown variation of the standard deviation. The solution was flexible and not explicit as might have been expected from the Paper.

Mr Thompson thought that formulae (1) and (2), which were very important, could be rounded off without significant loss of accuracy. The second decimal place suggested a precision which was unreal, and he suggested that the first might be written $\frac{R}{\sigma} = 0{\cdot}6N^{\frac{3}{4}}$ and the second $\frac{S}{R} = 1 - \sqrt{\frac{(M-B)}{\sigma}}$. That change would avoid giving any false ideas about a high degree of accuracy. The value of N, the number of years for which the calculation was taken, was, after all, rather arbitrary. There was no particular magic about 100 years; it was perhaps a useful period, but he agreed with previous speakers that circumstances would have to have a considerable influence in determining the amount of

storage, and therefore it was not necessary to go to any great niceties to get the starting figure.

From the figures given in the Paper it appeared that the storage for the Nile was about three times the mean flow to give nearly the mean discharge. He had tried the same methods of calculation in respect of the flow of the river Derwent in north Derbyshire, for which 50 years' fairly accurate gaugings of flow were available, corrected, of course, for changes in storage. He found that the value of the standard deviation was 0·159 of the mean, that the value of R, the accumulated excess deficit, was 7·5 times the mean, not 16·5, and that the value of K was only 0·623. Taking those figures, it would be found that instead of three times the mean flow about twice the mean flow would be required to equate to the same degree. In Britain the storage was usually about 0·6 of the mean flow of a stream and about 0·8 of the mean was aimed at as the reliable discharge. Those figures were comparable with what had been arrived at for the Nile.

Mr Thompson agreed strongly that the question of sustained discharge from a reservoir, or "reliable yield" (as it was called, rather incorrectly), was a question of probability, and that in that matter there was no certainty, but only a degree of risk.

Mr F. A. Sharman (a Senior Civil Engineer, Sir William Halcrow & Partners, Consulting Engineers) observed that the present Paper and its predecessors[1, 2] must have been studied with great interest by everyone who had to grapple with reservoir problems. The Author had brought together a great quantity of data, collected from nature and systematized with the object of helping engineers in the very uncertain business of forecasting weather for a hundred years or so. Any evidence which threw light on the vagaries of climate in past centuries might be of value, even when it originated in an American forest or at the bottom of a Russian lake.

The Author sought first to establish that annual river discharges varied in the same way as a number of other natural happenings, such as rainfall and temperature. In the present Paper, the evidence adduced for that proposition was rather scanty. At first sight Fig. 2, in which nearly 6,000 observations had conspired to produce a straight line, with significant departures only in the unlikelier parts, was a sensational step towards finding the single universal law of nature. In all those measurements, however, only 169 were actual water discharges. There were 176 lake levels and 799 river-gauge readings, which were more or less closely related to river run-offs, but those were unlikely to be linked with total catchment run-offs by a linear relation. The remaining 4,771 observations were temperature and rainfall readings at various single observation points. It was interesting to see how those last readings departed from their averages in just the way that sets of coins would do when tossed up, provided that the time sequence was ignored and the extreme values were disregarded. The trouble was that run-off was a totally different kind of end-product. Any particular catchment would combine rainfall distributions in a characteristic way, so that if the rainfalls were Gaussian the run-offs could not ordinarily possibly be so also. Lake levels and gauge heights were again quite different end-products, and in any ordinary catchment if discharges or free run-off water were Gaussian, the heights recorded could not follow the same distribution. To test those assertions the data in Table 2 was split up, and Roda gauge readings and lake levels combined with the two sets of discharge readings were plotted on separate frequency histograms and compared with the Gaussian curve. As expected, the shapes produced were markedly different from each other, and from the normal Gaussian curve, even allowing for the expected extra irregularity caused by the reduced number of observations. The straight line of Fig. 2 had in fact been produced by diluting the irregular data with large quantities of nearly random material.

But it was necessary to go back to the Author's original Paper,[1] and to his books on the Nile Basin,[5] in order to make a fair assessment of the evidence so far produced in justification of the claim that the basis of reservoir planning could usefully be broadened by analogy with other data. The most important evidence was possibly that the differen

classes of phenomena gave rather similar values of K in the expression $\log \frac{R}{\sigma} = K \log \frac{N}{2}$. The scatter of points, especially at higher values of N, certainly made it hard to assign different values to the constants for different classes, but led equally to the conclusion that the only thing the phenomena had in common was their anarchy. The acid test was—could R be forecast for a long term of years better from the formula than by weighing up the records available for a particular case? The applications, especially to actual flow records, were not very encouraging.

There was one respect in which the assortment of data presented did show a marked resemblance to river flows, though perhaps more to peak annual run-off rates than to annual totals. It was a common experience to find that annual maximum flood readings plot in a linear way on probability paper, except for the largest two or three readings, which had occurred long before they were expected. The usual procedure was to reflect that there must be one 50-year period in which the "once in 200 year" or "once in 10,000 year" flood came, and that must be the one. The curious thing was that it always seemed to be the one. If it was not in the record, it happened in the following year. In just the same way, the well-marked curves at the ends of the line in Fig. 2 suggested that the random distribution was a dangerous basis on which to estimate the probability of violent departures from the average value of many end-products of climatic variables.

The grouping of results in time, as much as the non-Gaussian distribution, was responsible for the unpredictability of flow phenomena. The Author said very little about climatic trends or cycles, although he cited Stockholm rain as an example of a varying mean, and he did help to kill the optimistic myth that 35-year-rainfall means were reliable for long periods. If, as seemed to emerge from Dr Kraus's recent Papers to the Royal Meteorological Society, there had been a well-marked decline in tropical rainfall in the twentieth century, compared with 1860–1898, and corresponding remarkably with the reduction in Nile flow, it was clear that many areas were vulnerable to long-lasting shifts in the balance of the evaporation-precipitation cycle. In addition, although it was not fashionable to discern cycles in run-off data, such recurrences had certainly been recorded. Whatever reservations must be made about the probability of such cycles being repeated, it would have been very interesting if the time distribution of the long-term records alluded to in the Paper could have been produced. A rough qualitative indication of the relative amplitudes of climatic trends and cycles, and any evidence of periodicities by harmonic analyses, might be the most significant contribution which the tree-ring and lake-varve data could make to that subject.

Very long-term records indicative of run-offs or climates, whether of human origin or deduced from natural structures, must be viewed with great caution. In particular, the run-off of a catchment would certainly be affected by vegetation changes, and by erosion and silting, as well as by variations of rainfall and evaporation. Those changes would often take the form of irreversible trends, from which the deduction of formulae to cover future behaviour would be inadmissible.

If it was true that river discharges did not belong to the same family of distributions as the assortment of other phenomena, but had a special pattern which was different for each catchment, climate, and perhaps for every century, then it could not be of much help to try various types of regulation on selected records in order to deduce general formulae for capacity and to recommend different types of regulation. It was notable that some of the most refractory of the Author's phenomena were the few genuine discharge readings which had been included. The Author had conducted a fascinating expedition in search of analogies between natural phenomena, but necessary and enlightening as the search had been, Mr Sharman did not think the analogies had been discovered. It would be necessary to revert to the painstaking study of each individual case, weighing the climatic oscillations and trends, the run-off factors and intensity distributions, the probable sizes and durations of rainstorms, and whatever records might have survived. The promising short cut offered by statistical comparisons had turned out to be a cul-de-sac.

Mr N. J. Cochrane (a Senior Engineer, Sir William Halcrow & Partners, Consulting Engineers) said he had the impression that the Author had begun to be carried away into a limbo of randomness, but had realized that something was wrong and had withdrawn. In the introduction the Author said that things were not random, but in the Paper he went on to say that the data were distributed in a Gaussian manner. Where had he withdrawn to? Were things random or were they not? If the Author conceded that they were not random, Mr Cochrane suggested that they could only be under control. If they were under control, all that had to be found out was, under what kind of control? It was impossible to explain Ice Ages and the post-glacial Atlantic Optimum on a random basis. Some phenomena seemed to behave in a cyclic manner. It was not sufficient to say that for some reason high values tended to persist in grouping together, and low values also tended to group together.

Mr Cochrane showed a slide in which he had plotted the Smithsonian solar constant, a measure of solar energy, against rate of change of sun-spots modified for rate of change in individual months. He had deduced that relation as a result of a disturbance hypothesis about climates. The inference was clear, namely, that when the sun-spots were changing most rapidly, irrespective of their number, the solar constant was highest, or in other words the solar energy tended to be highest. He went on to consider in a second slide the behaviour of Lake Victoria and the Nile and Lake Nyasa and the Shire, two similar large lakes, and to plot the rate of change of sun-spots against the free water of those systems. A markedly cyclic arrangement was observed and the interesting fact was that cycles in the rate of change of sun-spot curves, and the cycles in the Nyasa Shire complex and in the Victoria Nile complex were all happening at about the same time.

It had been contended that the Lake Victoria sun-spot analogy had broken down some time ago, but it was the method of analysis which had failed. Originally the comparison had been made between the lake level, which was meaningless, with actual numbers of sun-spots, which were probably meaningless also. If, however, total free water was plotted against rate of change of sun-spots, a demonstrably cyclic phenomenon could be exhibited. The difficult thing to explain was why, if the Victoria Nile was demonstrably cyclic, was the Aswan Nile not so. Mr Cochrane could not explain that; but he had analysed a number of phenomena on his disturbance basis and found them to be cyclic, but the relation was sometimes very complex and he had much further to go yet. It would not be possible always to demonstrate cyclic phenomenon and, in any event, it took a long time to sort out what was important and cyclic in the data.

He thought that the Author had demonstrated that there was a remarkable non-random uniformity in the behaviour of certain natural phenomena. Mr Cochrane invited the Author to cast away all the statistical heresy, because he thought it hid more than it revealed and there were easier methods of presentation.

With regard to Stockholm rainfall, was not it a fact that that was largely snow? How was snow measured as water scientifically so long ago? If it was mostly snow, did it invalidate effectively Binnie's conclusion that 35 years was a reasonable period to choose? Secondly, the Roda gauge was quoted in the Paper as a level, and an earlier speaker had said that levels did not mean much. Perhaps curves were available which would give some idea of the actual amount of water. If it was merely a level Mr Cochrane thought that it meant no more than a lake level. On the question of varves he would like to say a cautionary word. Just after the 1939–45 war he had had the privilege of seeing Dr Leo Casagrande (a German scientist) making artificial varves in clay at the Building Research Station without employing anything in the nature of a climatic succession.

Professor G. A. Barnard (Professor of Mathematical Statistics, Imperial College of Science and Technology) observed that apart from differences of inputs and the loss effects, the statistical theory of dams was the same as the statistical theory of stockpiling. The problems involved were similar, whether one was storing water or storing iron ore to be fed into a blast-furnace which must on no account be allowed to go out; they were

closely related to a branch of statistical theory which had developed a great deal, particularly during and since the war, under the name of the "theory of queues". After all, a queue differed from a reservoir only in the fact that whereas it was desired to keep a reservoir full, it was usually desired to keep a queue empty; but the fact that they both had inputs and outputs, and might have very complicated rules of control, meant that a great deal of the theory was common to both. All such problems depended on the branch of statistics known as the study of time series, in which semi-random phenomena in nature or in industry, or in other fields were studied.

With reference to that point Professor Barnard mentioned the work of Dr G. H. Jowett, of Sheffield, who had developed a tool which he called a variogram, which could be used for the analysis of time series of the types under discussion, getting away from the classical and rather outmoded tools of the type of the Schuster periodogram. The variogram was a real step forward, because it helped in the analysis of, and in giving sensible answers to, some of the problems which occurred in real life.

A considerable amount of theoretical work on dams had been carried out at Imperial College, since Mr P. O. Wolf had passed to them a Paper by the Author on water flows. Dr Anis had written his doctoral thesis on the theoretical analysis of the ranges and capacity of reservoirs which would be required for a random series of rainfalls.

Professor P. A. P. Moran, of the Australian National University at Canberra, had written a long series of Papers on the theory of dams and stockpiling, some of which had been published in the Australian Journal of Applied Science. Professor Barnard mentioned that Professor Feller, of Princeton, who had also written on the same topic, was in error in thinking that the difference between the index $N^{\frac{1}{2}}$, which would occur for a random series of independent rainfalls, and the values of K which the Author had observed could be accounted for by correlations in the series. It was possible to prove that no set of simple correlations could account for those figures, so that, in fact, the Author had shown that not only was the series of rainfall figures not random, but that no simple type of non-randomness could account for the figures. That was a fascinating problem for climatologists.

The fact that specially complex series of figures were involved in real problems did not mean that theoretical models could not help in their solution. It did mean that in constructing theoretical models and finding out what they did there was need for powerful computing facilities. Those were now becoming available with the development of automatic computing machines. Professor Barnard strongly supported the Author's suggestion that such machines could provide a link which would join up the practical studies of engineers with the more theoretical studies of statisticians.

Mr P. O. Wolf (Lecturer in Fluid Mechanics and Hydraulic Engineering, Dept of Civil Engineering, Imperial College of Science and Technology) observed that when the Author's first Paper[1] had appeared about 5 years earlier, he had endeavoured to obtain a grasp of the Author's thesis. The first Paper[1] was epoch-making in the sense that it represented a great step forward from the purely numerical treatment of time series of hydrological data.

In view of the doubts thrown on the usefulness of statistics in that field, earlier in the discussion, Mr Wolf emphasized his conviction that the ultimate aim of scientific analysis was the complete understanding of physical phenomena and their connexion. The Author, as a physicist, and as the man who for many years had obtained by measurement in the Nile Basin as many and as great a variety of hydrological data as possible, would no doubt share that ultimate aim. At present, however, few, if any, of the connexions between the many hydrological causes of reservoir yields were established numerically. Yet water-supply schemes of vital importance to whole nations had to be designed and constructed and, with the present scientific apparatus, the application of proper statistical methods appeared to give the most reliable results, particularly if the general behaviour of a scheme—as distinct from possible extremes—was to be studied.

It should be noted, in parenthesis, that statistical methods were commonly employed even in the application of rigorous physical theory to hydrological phenomena.

The great merit of the Author's treatment lay in his mathematical description of the grouping of hydrological data which, without regard to their sequence, followed the normal frequency distribution of Gauss. Purely random events, such as the results of the tossing of coins, had been described by Professor Barnard as due to "a penny not possessing a memory"; the chances of obtaining "heads" or "tails" were independent of previous results. Hydrological data, however, did possess such a "memory", as defined by the Author's storage index K or by Mr Gold's "persistence factor", and equation (1) enabled engineers to make use of it, for example, in reservoir calculations. There was no suggestion of K being constant for all natural phenomena, even of one class, but it tended towards a single value of practical utility if applied to various series of data of one single hydrological phenomenon. At first sight the use of the storage index K appeared more convenient in reservoir calculations than that of the persistence factor, whose utility seemed to be greater in weather analysis and forecasting.

Turning to the details of the Paper, Mr Wolf referred to the departure from the "normal" distribution at the extremes of the range plotted in Fig. 2; he, too, had doubts on the extremes to be forecast from series of natural data. In practice, however, Fig. 2 would not be alarming, since it indicated only that the computed value R of reservoir storage to be provided might be inadequate if periods exceeding $N = 500$ years were considered.

The vast amount of computational work which the Paper must have involved was fully appreciated by Mr Wolf. Even so, he would suggest to the Author that much more work would be required to complete the picture, and in order to enable others to make similar studies he asked that Tables of the Author's raw data be included as an Appendix.

To make some of the Tables more comprehensive, the Author might have used a method demonstrated in an important Paper by Thompson.[6] There the available time series had been repeated, giving a continuous series of $2N$ data, and the analysis based on the first n years and extending over a range of N years could be started at any point in the original time series. Such treatment was understood to be sound from the point of view of statistical theory for it used the original data, so far as possible, in their original sequence. If applied to Table 4 and to the work described on pp. 537–540, it made the results independent of the accidental position of the starting date in the series, and would increase the significance of the conclusions. He noted that the Author had used moving starting points to arrive at Table 11, and Mr Wolf was not suggesting that anything but the formidable labour required had prevented such a technique being used everywhere. If a computing machine could be devised which would allow such intricate operations as the Author's regulation 9 to be carried out mechanically, the additional work suggested would become practicable.

Lastly, Mr Wolf offered some comments on the variations in the Author's storage index K. He asked the Author if it would not be expected that, since the number of data became very large indeed and the frequency distribution (irrespective of sequence) remained "normal", the effect of small groups might decrease so that the value of K would tend to 0·5. If K remained considerably larger than 0·5, the time series would presumably be subject to long-period fluctuations associated in nature with changes in climate. Such climatic changes would cause even reservoirs designed for century storage ($N = 100$) to produce guaranteed drafts B which altered with the mean M of the previous inflows

The interesting comments by Mr Allan and Mr Thompson had well described the effec of losses on the behaviour of real reservoirs. Losses in fact represented a variable increase in draft, corresponding mathematically to regulation 9. Depending on the rate o increase of losses with reservoir depth and surface area, such losses might, in practice put an upper limit to the storage volume which the inflow was capable of filling. In tha sense, variable losses appeared to lead to a reduction in the value of the storage index K

On p. 534, the Author had mentioned the effect of the variability of head on the hydro electric output from a low- or medium-head scheme. In a country with low evaporatio loss, such as Scotland, the greatest output of electrical energy resulted from a regulatio keeping the water level high and risking loss of water over the spillway. Such woul not be the case with a scheme like the proposed high Aswan Dam where too high a mea

water level would cause excessive evaporation loss, and where the optimum depth H for power production might be expressed as:

$$H = \frac{(M - AL)}{LdA/dH}$$

where M denoted the mean inflow per year
A „ the surface area of the reservoir at depth H
and L „ the loss (depth per unit area of the reservoir surface) per year.

Where there were considerable seasonal variations—as at Aswan—that formula would naturally be expanded to take account of them.

*** **Mr David Lloyd** (Liverpool Corporation Waterworks) asked the Author to comment on the effect of variation within the years. The analysis used annual values and Mr Lloyd had found in practice that monthly and daily values of small rivers modified the draft that could be guaranteed by about 5%.

For comparison, he had applied the Author's method to the data of the Rivington Catchment, which had been impounded for 100 years as one source of supply to the City of Liverpool. The published data were that the long-period run-off averaged about 5,900 million gal/year; and, with the available storage of 3,800 million gal, the safe yield was 15½ to 16 million gal/day.

The period 1932–1955 had been analysed by the Author's method, giving the following figures, in millions of gallons. For the 24 years, $M_{24} = 7{,}210$, $R_{24} = 7{,}540$, and the sample standard deviation was 1,490 giving an estimated $\sigma = 1{,}640$.

Case 1. Full storage $S = 3{,}800$; thence $S/R = 0{\cdot}50$, which from equation (2) = $0{\cdot}94 - 0{\cdot}96\sqrt{\frac{(M - B)}{1{,}640}}$

The solution gave $B = 6{,}095$, which indicated that a draft of 16·7 million gal/day could be guaranteed.

Case 2. Starting with $S = 2{,}280$; then $S/R = 0{\cdot}30$ and from equation (2), $B = 5{,}865$. That was, the guaranteed draft was 16·1 million gal/day higher than that which might be expected to empty the storage.

Those values were comcomitant with a constant draft regulation; Mr Lloyd endorsed the Author's view that regulation 9 was the type which would be most generally useful, in fact one which was being forced upon Liverpool owing to high industrial demand.

Mr R. P. Black (Scientific Consultant, Ministry of Public Works, Egypt) referred to the Author's statement that natural events only formed a normal frequency distribution when their order of occurrence was ignored. High and low values tended to group much more than in the case of random events and the mean of a sample did not approximate towards the true mean as the size of sample increased—in fact, there was no true mean.

The Author had also shown that the storage required to give the mean each year for N years could be derived from equation (1) on p. 521, in which K had a mean value of 0·72, whereas for random events the corresponding equation was the previous one on p. 521: i.e., $R = 1{\cdot}25\sigma\sqrt{N}$.

If a draft B less than the mean was maintained, the required storage S could be found from the first of equations (2) (p. 522).

The equations for R and for log R/σ on p. 521 provided values of R which did not differ widely if N was less than 50 years, but, as N increased, so did the difference; thus for 100 years the values of R obtained from those equations were $16{\cdot}8\sigma$ and $12{\cdot}5\sigma$—a very considerable difference which increased steadily as N increased. It was interesting to note that the K of the Author's equation (1) had a normal frequency distribution;

*** This and the following contributions were submitted in writing upon the closure of the oral discussion.—Sec.

moreover, from the tree rings and varves data, which were the only really long-period data available, K appeared to be random, and hence the mean value of 0·72 was significant, unlike the mean value of a natural event. Now that was a matter of great importance. Irrigation projects were normally based on the experience of quite a short period of years (30 to 50), for the simple reason that no more data were available, and the Author's investigation appeared to show that the mean of those years had no particular significance when a long series of future years was under consideration and that, when storage to give the future mean over a long period of years had to be computed, a value of 0·72 for K in equation (1) was preferable to any value found from the sample of years available.

The labour involved in the Author's computations could be appreciated only by actually carrying them out for one single phenomenon, but had been fully justified by the result that the K of his storage-value equation appeared to be random and therefore that the best value of it was the mean 0·72 of all the computations.

When everything was known in advance the regulation of a "century storage" reservoir was a press-button affair; only the required initial content had to be computed and that was easy because by starting with any assumed value of the initial content, the computation would eventually lead to the required starting content, which was to be repeated at the end of each filling and emptying cycle.

In practice, however, nothing was known of the future, not even the mean to be expected; the starting point was a reservoir capacity calculated from equation (1) where $K = 0{\cdot}72$ and σ was the standard deviation of such observations as were available, and it was required to give the *future* mean over some period of years.

The Author had devoted the major part of the Paper to the solution of that problem. With only the knowledge that a series of high years was just as likely as a series of low years after starting, he began naturally with his reservoir half full, and, by patient trial and error over about fifty different phenomena, he concluded that a regulation with a draft, varying both with the inflow and the reservoir content, would give the most favourable results, in that there was then the smallest chance of the reservoir emptying. For no considerable period was the draft kept steady, but the large annual fluctuations were definitely avoided, and variations of draft were in fact reduced to such as might reasonably be absorbed in the elasticity of crop requirements. For irrigation purposes with a fixed area of cultivation it was not of course necessary to have a steady supply year after year. If the supply was known at the beginning of the year and was within the limits of possible variation of crop requirements, that was sufficient, thus the solution the Author obtained was a sufficient solution, though it differed much from the original idea of distributing the mean each year over a long period.

The Author had paid much attention to the need to avoid emptying the reservoir, and cut down his draft as the reservoir contents fell to achieve that purpose; it was, however, obvious that such a regulation would cause earlier spilling when the reservoir filled again since the capacity was limited.

Now, assuming that the reservoir served the dual purposes of power and irrigation, if it was as large as could be made, then the power interests would not be unduly perturbed at the spilling of water; but if such spilling occurred within the memory of the restrictions imposed to avoid emptying, it would be hard to convince the farmers that the restrictions, practised at their expense, were not in fact the cause of the spilling, and that the economies, far from being necessary, had actually caused future waste of water.

If the total supply came from two uncorrelated sources, and storage was available in both, then the chances that both reservoirs would empty together would be very small.

In the case of the Nile, there was no correlation between the Blue Nile and Bahr el Jebel, and only a small correlation (0·4) between the Bahr el Jebel and the Main Nile, so it might be an advantage in the ultimate conservation of the Nile to have as much storage as possible in the Great Lakes, in addition to the storage on the Main Nile. Since, however, the Bahr el Jebel mean discharge amounted to only about one-seventh of the Main Nile, storage at the lakes could play only a minor part and its use to supplement Main Nile storage in emergency might be a very costly business.

The ultimate conservation of the Nile involved of course the provision of power for industrialization as a major objective, and the regulation of over-year storage might be expected to produce conflicting demands from agriculture and industry. Thus, the satisfaction of irrigation requirements, in a long series of low years would cause a continuous reduction of the power available for industry, and some such procedure as the Author adopted to prevent the reservoir emptying might possibly be acceptable, as a compromise, to both interests.

Mr Naguib Boulos (Director of Observations, Nile Control Department, Cairo, Egypt) observed that the equation $R/\sigma = (N/2)^k$ had been found to be the best fit for the physical phenomena. The average value of k for 690 cases of physical series of observations had proved to be 0·73 whilst the individual values of k ranged from 0·46 to 0·96. That formula was likely to be applied when it was desired to know the capacity of a reservoir required to equalize the output for a certain number of years, usually 100, with the aid of the standard deviation σ of the phenomenon deduced from observations made in the past.

On the question of the project of Sudd-el-Aali (or High Dam) Reservoir on the Nile, the value of k for the period 1870 to 1955, for the quantity of water passing Aswan, had proved to be 0·89 which was very near to the maximum value of k ever observed. A question which naturally arose was whether the average value of k for the 690 cases or the actual value of R calculated for the phenomenon of the discharges of the Nile at Aswan should be adopted to forecast the future discharge and storage. There were only 86 years in the record and the actual value of R should be raised by some means to correspond to the number of years required to be equalized and, in that special case, 100 years was thought convenient. The answer to that question might be found in the very long records of observations of physical phenomena.

If R and σ were known for a certain period of a physical phenomenon, a forecast could be made of what would happen in the next period, either (1) by the aid of the standard deviation for the past period and the law $R/\sigma = (N/2)^{0\cdot73}$ thus enabling the prediction of R_{100}, or (2) by using the standard deviation of the past period and the value of k derived from the same past period to predict R_{100}. In order to judge which was a better prediction, the long series of physical phenomena, divided into periods had been used in Table 12 to give the deviations of the mean value of k (= 0·73) from the actual value for the phenomenon in the sub-division of the period as well as the difference between the value of k calculated for the preceding subdivision and the actual value of k of the subdivision. In some cases the 0·73-value of k and in others the preceding value of k was nearer to the actual. The square deviation from the actual was calculated for both cases of prediction; and the probable error of a single observation was calculated for each phenomenon from the formula:

$$\text{Probable Error Single Observation} = \pm \frac{2}{3}\sqrt{\frac{\Sigma d^2}{n-1}}$$

where Σd^2 was the sum of the square deviations from the actual and n was the number of observations.

All the data used in the Author's original research on "Long-Term Storage Capacity of Reservoirs"[1] were used in that comparison of both predictions whenever there were subdivisions of periods, nearest to 50 years.

For 16 out of 19 individual physical phenomena, the probable error of a forecast made from $k = 0\cdot73$ was found to be less than the probable error of the forecast made from the value of k derived from the preceding period.

When all the 19 phenomena comprising 184 subdivisions were dealt with together, the probable departure of a single observation of k from 0·73 was $\pm$ 0·060 whilst the probable error of those derived from the preceding periods was $\pm$ 0·075; and thus it was concluded that using the constant 0·73 for a prediction of any given period of a physical phenomenon or group of periods of the phenomena was safer than using the special value derived for the preceding period of the same phenomenon; and in the special case of the Sudd-el-Aali

TABLE 12.—LONG SERIES OF PHYSICAL PHENOMENA

Error in taking k as 0·73 compared with the error in predicting k from its preceding actual value

Phenomenon	Period from	Period to	N years	Actual k	Probable error in taking k as 0·73	Probable error in predicting k from its preceding actual value
1. Water levels: small lake on Dalaven . .	1765	1808	44	0·84	± 0·075	± 0·109
	1809	1852	44	0·65		
	1853	1896	44	0·59		
	1897	1940	44	0·71		
			176			
2. Water levels: maximum Nile gauge at Roda	641	740	100	0·68	± 0·050	±0·074
	741	840	100	0·65		
	841	940	100	0·74		
	941	1041	100	0·65		
	1042	1142	100	0·82		
	1143	1242	100	0·86		
	1243	1344	100	0·72		
	1345	1445	100	0·78		
	1446	1741	100	0·69		
	1742	1866	100	0·84		
	1867	1946	80	0·75		
			1,080			
3. Rainfall: Stockholm . . .	1785	1824	40	0·84	± 0·044	± 0·056
	1825	1864	40	0·73		
	1865	1904	40	0·76		
	1905	1946	41	0·73		
			161			
4. Rainfall: Padua .	1764	1806	43	0·81	± 0·068	± 0·124
	1807	1849	43	0·78		
	1850	1892	43	0·59		
	1893	1934	42	0·77		
			171			
5. Rainfall: Milan .	1764	1789	24	0·68	± 0·075	± 0·300
	1790	1813	24	0·55		
	1814	1837	24	0·63		
	1838	1861	24	0·77		
	1862	1886	25	0·69		
	1887	1911	25	0·57		
	1912	1936	25	0·77		
			171			
6. Rainfall: Zwanenburg . . .	1735	1787	53	0·70	± 0·069	± 0·075
	1788	1840	53	0·77		
	1841	1893	53	0·67		
	1894	1945	52	0·57		
			211			

TABLE 12.—LONG SERIES OF PHYSICAL PHENOMENA—*Contd*

Phenomenon	Period from	Period to	N years	Actual k	Probable error in taking k as 0·73	Probable error in predicting k from its preceding actual value
7. Temperature: New Haven .	1781 1822 1863 1904	1821 1862 1903 1945	40 41 41 42 164	0·87 0·71 0·78 0·84	± 0·072	± 0·087
8. Temperature: Paris . . .	1764 1805 1846 1887	1804 1845 1896 1930	41 41 41 44 167	0·88 0·66 0·69 0·73	± 0·066	± 0·106
9. Temperature: Berlin . . .	1769 1811 1853 1896	1810 1852 1895 1938	42 42 43 43 170	0·77 0·65 0·61 0·56	± 0·087	± 0·064
10. Temperature: Stockholm. .	1899 1764 1809 1854	1942 1808 1853 1898	43 45 45 45 178	0·74 0·71 0·77 0·68	± 0·017	± 0·053
11. Temperature: Zwanenburg .	1735 1788 1841 1894	1787 1840 1893 1945	53 53 53 52 211	0·68 0·70 0·55 0·59	± 0·091	± 0·074
12. Annual growth of trees: Medow Valley . . .	1620 1670 1720 1770 1820 1870	1669 1719 1769 1819 1869 1919	50 50 50 50 50 50 300	0·90 0·80 0·74 0·91 0·71 0·85	± 0·085	± 0·107
13. Annual growth of trees: Pike's Peak . . .	1570 1620 1670 1720 1770 1820 1870	1619 1669 1719 1769 1819 1869 1919	50 50 50 50 50 50 50 350	0·75 0·88 0·91 0·64 0·62 0·79 0·69	± 0·077	± 0·107

TABLE 12.—LONG SERIES OF PHYSICAL PHENOMENA—*Contd*

Phenomenon	Period from	Period to	N years	Actual k	Probable error in taking k as 0·73	Probable error in predicting k from its preceding actual value
14. Annual growth of trees: Flagstaff Pines . . .	1400	1449	50	0·87		
	1450	1499	50	0·69		
	1500	1549	50	0·76		
	1550	1599	50	0·79		
	1600	1649	50	0·86	± 0·076	± 0·072
	1650	1699	50	0·82		
	1700	1749	50	0·86		
	1750	1799	50	0·83		
	1800	1849	50	0·73		
	1850	1899	50	0·92		
			500			
15. Annual growth of trees: Sequoia.	1000	1049	50	0·91		
	1050	1099	50	0·90		
	1100	1149	50	0·79		
	1150	1199	50	0·68		
	1200	1249	50	0·82		
	1250	1299	50	0·64		
	1300	1349	50	0·56		
	1350	1399	50	0·82		
	1400	1449	50	0·88		
	1450	1499	50	0·93	± 0·081	± 0·096
	1500	1549	50	0·61		
	1550	1599	50	0·79		
	1600	1649	50	0·74		
	1650	1699	50	0·77		
	1700	1749	50	0·86		
	1750	1799	50	0·77		
	1800	1849	50	0·84		
	1850	1899	50	0·94		
			900			

TABLE 12.—LONG SERIES OF PHYSICAL PHENOMENA—*Contd*

Phenomenon	Period (A.D. positive B.C. negative) from	to	N years	Actual k	Probable error in taking k as 0·73	Probable error in predicting k from its preceding actual value
6. Thickness of annual layers of mud: Lake Saki, Crimea .	— 2090	— 2041	50	0·65		
	— 2040	— 1991	50	0·78		
	— 1990	— 1941	50	0·83		
	— 1940	— 1891	50	0·74		
	— 1890	— 1841	50	0·66		
	— 1840	— 1791	50	0·67		
	— 1790	— 1741	50	0·71		
	— 1740	— 1691	50	0·64		
	— 1690	— 1641	50	0·69		
	— 1640	— 1591	50	0·66		
	— 1590	— 1541	50	0·77		
	— 1540	— 1491	50	0·69		
	— 1490	— 1441	50	0·61		
	— 1440	— 1391	50	0·56		
	— 1390	— 1341	50	0·68		
	— 1340	— 1291	50	0·58		
	— 1290	— 1241	50	0·64		
	— 1240	— 1191	50	0·73		
	— 1190	— 1141	50	0·69		
	— 1140	— 1091	50	0·72	± 0·049	± 0·058
	— 1090	— 1041	50	0·68		
	— 1010	— 991	50	0·78		
	— 990	— 941	50	0·60		
	— 940	— 891	50	0·69		
	— 890	— 841	50	0·75		
	— 840	— 791	50	0·63		
	— 790	— 741	50	0·72		
	— 740	— 691	50	0·68		
	— 690	— 641	50	0·66		
	— 640	— 591	50	0·71		
	— 590	— 541	50	0·78		
	— 540	— 491	50	0·66		
	— 490	— 441	50	0·70		
	— 440	— 391	50	0·71		
	— 390	— 341	50	0·64		
	— 340	— 291	50	0·71		
	— 290	— 241	50	0·81		
	— 240	— 191	50	0·69		
	— 190	— 141	50	0·86		
	— 140	— 091	50	0·75		
			2,000			

TABLE 12.—LONG SERIES OF PHYSICAL PHENOMEMA—*Contd*

Phenomenon	Period (A.D. positive B.C. negative) from	to	N years	Actual k	Probable error in taking k as 0·73	Probable error in predicting k from its preceding actual value
17. Thickness of annual layers of mud: Moen Sogn district, Norway . .	− 100	− 51	50	0·76		
	− 50	− 1	50	0·81		
	0	51	50	0·76		
	52	101	50	0·78		
	102	151	50	0·79		
	152	201	50	0·68		
	202	251	50	0·63		
	252	301	50	0·78		
	302	351	50	0·61		
	352	401	50	0·68	± 0·046	± 0·055
	402	451	50	0·72		
	452	501	50	0·66		
	502	551	50	0·58		
	552	601	50	0·72		
	602	651	50	0·79		
	652	701	50	0·75		
	702	752	50	0·74		
	753	802	50	0·71		
	803	852	50	0·80		
	853	902	50	0·78		
			1,000			
18. Thickness of annual layers of mud: Tamiskaming, Canada .	0	49	50	0·73		
	50	99	50	0·63		
	100	149	50	0·80		
	150	199	50	0·60		
	200	249	50	0·72		
	250	299	50	0·76		
	300	349	50	0·70		
	350	399	50	0·72		
	400	449	50	0·76		
	450	499	50	0·72		
	500	549	50	0·84		
	550	599	50	0·84	± 0·067	± 0·097
	600	649	50	0·80		
	650	699	50	0·72		
	700	749	50	0·50		
	750	799	50	0·77		
	800	849	50	0·77		
	850	899	50	0·67		
	900	949	50	0·95		
	950	999	50	0·77		
	1000	1049	50	0·54		
	1050	1099	50	0·72		
	1100	1149	50	0·80		
	1150	1199	50	0·86		
			1,200			
19. Sunspot numbers	1751	1788	38	0·70		
	1789	1826	38	0·79		
	1827	1864	38	0·65	± 0·035	± 0·055
	1865	1902	38	0·72		
	1903	1940	38	0·72		
			190			

Reservoir on the Nile, it would be safer to adopt the factor 0·73 than to adopt the exceptionally high value derived from the actual discharges of the Nile.

Mr A. R. Thomas (a Consultant) observed that although the Paper was mainly concerned with long-term storage in reservoirs the Author's comprehensive analysis of natural data, some of which extended over several centuries, represented a notable contribution in the broader sphere of hydrology and some of his results and conclusions were of considerable general interest.

In particular might be mentioned the conclusions in regard to the tendency of annual values of natural phenomena to occur in groups. It was to be noted that the natural data used by the Author related to quantities which varied primarily as a result of meteorological conditions, mostly rainfall. Whilst it was generally recognized that meteorological data, particularly rainfall, exhibited a degree of "grouping" in excess of that expected in purely random variations, no defined pattern had so far been established. The question was of vital concern in connexion with the use of frequency analyses in the estimation of probabilities of events, for example annual maximum flood discharges and catchment yields, and the Author's treatment of very extensive series of data by the method of accumulative deviations was of great interest.

Before conclusions were drawn in the broader sphere, however, it was pertinent to consider the following questions:—

(1) To what extent were the Author's conclusions applicable where the frequency distribution did not conform to the Gaussian normal?
(2) What was the physical explanation of the pattern of occurrence?
(3) Was the characteristic confined to meteorological phenomena or could it be detected in other natural data?
(4) What value should be placed on the Author's long-term data in drawing conclusions relating to rainfall?

The Author's conclusions, put forward in his earlier Paper[1] and amplified in the present Paper, to be examined in the light of those questions were, briefly, that there was a tendency to grouping in the order of occurrence of annual data as a result of which the relation $R/\sigma = 1{\cdot}25N^{0{\cdot}5}$ for random events was replaced by $R/\sigma = 0{\cdot}61N^{K}$, where K had a mean value of 0·72, and further that the mean and standard deviation computed for short periods were more variable than was the case in random distributions.

With regard to the first question, it was to be noted that the Author's data when expressed in terms of arithmetic deviations from arithmetic means were not markedly skew and when combined in Fig. 2 appeared to conform closely to the Gaussian normal distribution. That was not quite typical of annual rainfalls in general and was certainly not typical of all meteorological data.

The Author's data were statistically of two different types:

(i) sum totals or means of a continuous variable over fixed intervals, namely, annual rainfall, annual volumes of river discharge, tree rings, and varves; and
(ii) extreme values of a continuous variable within fixed intervals, namely, annual maximum river levels and discharges, temperatures, and pressures.

Data of the former type might have normal or skew distributions; rainfall frequently displayed a marked skewness. In the case of (ii) the distributions derived by Fisher and Tippett[7] indicated that a skew distribution of a logarithmic type was to be expected for extreme values.

It was general experience that annual maximum discharges were skew in distribution, often approximating as might be expected to the logarithmic normal. River gauge readings varied primarily with discharges, but since the gauge/discharge curve generally followed a relation of the type: $Q = CY^n$ where Q was the discharge, Y the water level above a suitable datum, and C and n depended on the hydraulic characteristics of the river, n having a value exceeding unity, it was evident that any positive skewness of the

discharge data was reduced in the transformation so that gauge readings might have a positive or a negative skewness. Any tendency for maximum gauge readings to follow a Gaussian normal distribution, as in the case of the Roda gauge, must be fortuitous.

Since it must be accepted that data might be markedly skew it would be of value if the Author were to express his views on the effect of skewness on his conclusions and on the use of his equations, both in the general concept and in the specific application to reservoir storage.

With regard to question (2) a rational explanation was always a desirable supplement to results determined statistically, even though it might not be very specific. A very general explanation of the tendency to "grouping" in the order of occurrence of meteorological phenomena could be found in the physical origins of the phenomena. There were in the atmosphere many continuously varying influences, some constant or with slow secular trends, some cyclic such as those of solar origin and others emanating from preceding patterns. It followed from the Central Limit Theorem of Laplace [8, 9] that if a variable depended equally on an infinite number of independent influences, its frequency distribution would be that of the Gaussian normal. In the case of meteorological phenomena, however, though the number of influences might be great they were not equal in effect or persistence, so that the sequence of values in a series of data was not in general completely random. In particular, owing to inertia to change, a dominating influence on the conditions at any instant were the conditions immediately preceding, and that was a cause of persistence in a series of data. Mr Thomas said he would leave to others more competent the explanation of persistence in annual values, outliving the seasonal changes, but it was conceivable that that could be appreciable and the Author's data showed evidence of it.

The degree of persistence depended on the rate at which the influence of a factor diminished, and that was a time factor. That point was well illustrated by the example of fluid turbulence, a phenomenon which could occur quite independently of any meteorological origin but which displayed a similarity in physical characteristics in that the dynamic pattern resulted from a random mixing. The instantaneous velocity of turbulence at a point depended on preceding conditions at the same point and elsewhere so that a degree of autocorrelation existed between the successive values in a series of observations. In the discussion on the Author's previous Paper[1] L. M. Laushey contributed some very interesting data of velocity measurements in a stream of water taken at $\frac{1}{5}$-sec intervals. The deviations of velocity-squared fluctuations when treated according to the Author's procedure indicated a value of the index K of approximately 0·65. The value of K was no doubt closely associated with the degree of autocorrelation, which if positive amounted to persistence, and that depended on the time interval between measurements relative to the scale of the turbulence. Had the measurements been taken at $\frac{1}{100}$-sec intervals there would have been greater correlation between consecutive values and the value of K would have been nearer unity, which appeared to be the limit for perfect correlation. On the other hand had they been at 5-sec intervals the values observed would have been almost random in sequence and the value of K would have approached 0·5.

There must similarly be a time scale in the change of annual pattern in meteorological phenomena and that would be revealed if a number of series of data were analysed to determine the degree of persistence. The Author's data showed evidence of persistence periods of several years (see Fig. 3) whilst McIllwraith,[10] whose data approximated to the logarithmic normal distribution, found a tendency in short periods of rainfall records for a clustering of the years in which the standard deviation was either abnormally high or low, but expressed the opinion that that tendency disappeared over long periods, e.g., 50 years.

Engineers who had to base estimates of probability on data of relatively short periods required a more precise indication of the effective period of persistence in annual rainfall data and the probable error of a short-term mean. Approaches which might prove fruitful were:—

(1) Study of the trend of standard deviations of means of consecutive annual rainfalls as the period included in the means increased, e.g., 1, 2, 5, 10, 20-year means.

(2) Computation of the coefficients of autocorrelation:

$$r_j = \frac{N\Sigma x_i x_{i+j}}{(N-j)\Sigma x^2}$$

for various values of j, where x_i was the deviation of any year's rainfall from the mean, x_{i+j} that of a year j years later, and N was the number of terms; the trend of r_j with increasing j would indicate the average period over which persistence was significant.

(3) Study of the trend of the Author's K, calculated for successive years, alternate years, every fifth year, every tenth year, etc.

Each method would involve a great deal of computation, but a real difficulty was that no rainfall records of very long terms were available, a difficulty evidently encountered by the Author in his research. Following his example, reliance would have to be placed on a large number of series of rainfall data of the longest terms available together with the few very long-term series relating to tree rings, varves, and the Roda gauge.

That led to consideration of the third and fourth questions. It was evident that persistence must exist in all data of continuous phenomena, natural or otherwise, if the values or pattern at one stage were a positive factor in the development of values at a subsequent stage; also that the degree of persistence depended on the circumstances. K would therefore differ in data of different types.

It seemed likely that the variations in tree rings, varves, and the Roda gauge resulted from variations not only of rainfall but also of other influences, such as climatic and soil conditions in the case of tree rings and varves. In the case of the Roda gauge there were two possible sources of variation which had apparently escaped notice. One was the effect of withdrawals of water for irrigation purposes upstream which must have varied from time to time; perhaps the Author would state whether that was a significant factor. The other was the dependence of the water level at Roda on the state of the Delta channels. During the thirteen centuries of records changes must have occurred in the number and pattern of those channels which would have been reflected in the specific gauges (i.e., readings corresponding to specified discharges) at Roda. Apart from a gradually rising bed there were no doubt alternating periods of rising and falling levels, causing variations in the means over short periods.

Rainfall was, however, probably the dominant influence in all three cases, and in the absence of long-term data of annual values the Author was justified in drawing conclusions from the data of those phenomena, but with the reservation that the value of K might have been affected by other influences. The possibility also existed that persistence in annual rainfall data might vary with geographical location.

Of particular interest in the analysis of the long-term data was the trend in the distribution near the extreme ends of the data. Fig. 2 showed a departure from the Gaussian normal at the extremes and the Author had attributed that to the small number of observations in the extreme groups and therefore the probability of error. That did not, however, explain why the same trend was seen in both curves. The method of calculating exceedence could be responsible for such apparent trends, whilst the high values in the upper curve were likely to have been affected by the flattening of the gauge/discharge curve at Roda for very high discharges. It would be helpful if the Author would illustrate this method of computing plotting points and also show separate curves for tree rings, varves, and the Roda gauge.

Mr W. B. Langbein (Hydraulic Engineer, United States Geological Survey) remarked that in view of the often sceptical attitude of statisticians toward reported non-random characteristics of natural phenomena, he was glad to read that in 1951 Wm Feller[11] had accepted the Author's discovery and had introduced more formal mathematical derivation of some of his equations. The discovery deserved to be exploited even though full explanation had not yet been attempted.

By way of further demonstration Mr Langbein had assembled several long records of American rivers. Fig. 17 showed a study of how the standard deviations of period means decreased with the lengthening periods. The zone labelled "Random data" defined a confidence band of one standard deviation about a line which showed the standard deviation to decrease as the square root of the number of data in the period means. Several stream-flow records were shown but since they did not generally exceed 85 years in length the standard deviations for period means longer than 20 years could not be obtained. And even then, there were only four means in an 80-year record so that the computation of standard deviation became rather uncertain, being subject to a standard error of about 35%. For 50- and 100-year means the results of computations by the Author[1] in 1951 were shown for the flood stages of the Roda gauge on the River Nile, for which there was a 1,000-year record. Also shown was the average of all of the Author's data based on long series of such natural phenomena as thickness of clay varves and tree-ring thicknesses. The significant thing about Figure 17 was that the points plotted above, or in the upper part

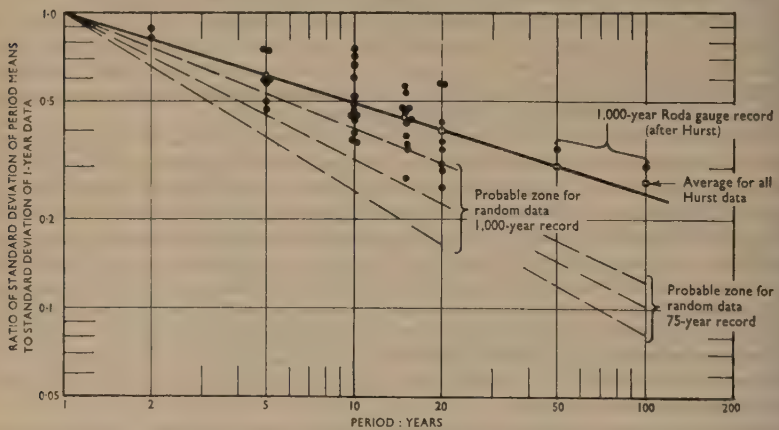

FIG. 17.—RELATIVE VARIATION IN MEANS OF HYDROLOGIC DATA

of, the random zone. But the grouping tendency for some phenomena as reflected in the group means was more marked than in others. It was very dominant in the flow of the Niagara River, which was highly regulated by the Great Lakes. The Columbia River record, for example, also showed it more strongly than the records of Lake Cochituate outlet in Massachusetts or those of the two European rivers. In fact, the data for the two European rivers were relatively close to random sequence.

Since most hydrologic data formed skewed distributions, the question had been raised whether the tendencies noted might be due to the skewness. The relationship $s_n = \frac{s}{\sqrt{n}}$ where s_n denoted the standard deviation of the means of n items and s the standard deviation of the individual items, was said to be distribution-free, which meant that it was independent of the form of the frequency distribution of the individual data. Rough checks had been made by rearranging the annual series for a few of the more skewed records of discharge by a randomizing process which had effectively destroyed any serial correlation tendency, but without change in the nature of their frequency distribution. In each test, the standard deviations had then fallen within reasonable limits above and

elow that defined by the relationship $s_n = \frac{s}{\sqrt{n}}$. Therefore, skewness should not be the ause of the tendency attributed to grouping.

The grouping tendency might be considered as a persistence phenomenon which might e expressed as correlation between years. If the correlation between successive years as r and if the correlation coefficient between flows n years apart was r^n, then

$$s_k = \frac{s}{\sqrt{n}}\left[1 + \frac{2r}{1-r}\left(1 - \frac{1-r^n}{n(1-r)}\right)\right] \quad . \quad . \quad . \quad . \quad . \quad (3)$$

s shown by Brooks and Carruthers in 1953 (see p. 326 of reference 12). A value of $= 0{\cdot}50$ fitted the observed points quite well for values of n up to 10 years; the graph nen tended to slope downward with a slope of 0·50, indicating that the serial-correlation ffect died out after 10 years. However, the data in Fig. 17 indicated no diminution in ne grouping effect, and so it had to be concluded that the persistence was more complex nan that due to simple serial correlation.

Because of the uncertainty in postulating the nature of the group persistence, the data Fig. 17 had been characterized by a simple line. At least it appeared reasonable that line which tended to average out the points in Fig. 17 was more apt to be representative f stream-flow data than the line that showed the reduction in standard error to vary nversely as the square root of the length of the period. For a working tool, a line which aried as the 0·28 power had been drawn, not so much to be representative of all records, ut to be more so than the square-root line. There was of course a danger that the comnon tendency in the position of the points in Fig. 17 might reflect the general correlation etween contemporaneous discharges of all streams in the United States previously iscussed, and that instead of many points there would be merely different expressions f the same experience, represented by the 80 years or so of the immediate past. There as no assured protection against that fault, except insofar as one was willing to accept he similar tendencies noted in the Author's data on diverse natural phenomena.

The persistence tendency in annual discharge, moreover, tended to make low the standard deviation as computed from a short-term record. The data in a short-term record ended to be more closely associated than in a long-term record, hence were a biased ample of the whole.

The Author had already observed, presumably for that reason, that the standard eviation of group means tended to be higher than if the data were random. If z denoted he ratio between the observed standard deviation of group means s_n and the standard eviation of group means calculated from the standard deviation of the total record s then:

$$z = \frac{s_n}{s/\sqrt{n}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Then since the total variance was equal to the sum of the component variances, the ariance and the standard deviation within each of the groups could be computed.

$$s_n^2 = s_N^2 \frac{(N-1)n - z^2(N-n)}{N(n-1)} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where s_n = standard deviation about mean of n data
s_N = standard deviation about mean of N data
n = number of data in a group
N = total number of data

If n be allowed to denote the length of a given record and N some great length of time, the right-hand side of equation (5) became independent of N and:

$$\frac{S_N}{s_n} = \sqrt{\frac{n-1}{n-z^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

That ratio then represented the amount of adjustment that had to be applied to the

standard deviation of a short-term sample to allow for the underestimate of variance du to the grouping tendency.

Length of record (years)	z	Adjustment to computed standard deviation
5	1·38	1·14
10	1·55	1·09
20	1·75	1·06
50	2·1	1·03
100	2·4	1·02

The bias appeared to be negligible for records of 20 years or greater length and in eac case the bias was less than the standard deviation of the standard deviation.

Shortness of record might introduce another form of bias, because a given period o record might not be representative of a long period. That form of bias could be mini mized through correlations with a long-term record in the general region. Simple propor tional adjustment was generally satisfactory.

Fig. 3 referred to the same tendency in somewhat different terms, and Mr Langbei would therefore welcome the Author's comments on his analysis. The Author's curv appeared to indicate higher corrections than did Mr Langbein's calculations. Ther were few records of stream flow sufficiently long to test the Author's curve for high ratio of N_2 to N_1, but using 75-year records with N_1 equal to 2 years, Mr Langbein found a cor rection factor to average about 1·25, in comparison with 1·44 as read from Fig. 3, an with 1·18 as computed from equation (6) for $n = 2$ and $z = 1{\cdot}13$ as determined fro Fig. 17 for $n = 2$. However, he deferred to the Author's earlier work and would welcom his analysis of those seeming differences.

Mr E. H. Lloyd (Imperial College) and **Mr A. A. Anis** (Chelsea Polytechnic observed that the problems posed by the Author, the methods he had used for thei solution, and the solutions themselves, were all of the highest interest, both in thei immediate practical consequences and in the theoretical work which they were un doubtedly destined to stimulate. Indeed some results of that stimulation could alread be seen.

In his 1951 Paper[1] the Author had arrived at the conclusion that the theoretical valu of the range, as a multiple of the standard deviation of the annual increments, would b $1{\cdot}25N^{\frac{1}{2}}$. At about the same time Feller,[11] using more refined methods, had arrive independently at exactly the same result. The Author had based his arguments o independent increments following the binomial distribution; Feller's result had gon further in that he had showed that *any* system of independent increments would lead t the same result, whatever their individual distributions.

The "range" referred to above was the difference between the greatest and the least o the accumulated departures from the observed mean. Feller called that the adjuste range, and he also considered the non-adjusted range, defined as the difference betwee the greatest and the least of the accumulated departures from the theoretical true mea (i.e., the so-called expectation). The important point of difference there was that if th individual increments were random variables, the observed mean from which the adjuste range was calculated was also a random variable; whereas the expectation was not random variable. The value of that expectation was of course unknown, and for tha reason the non-adjusted range had less practical application to the present problem tha had the adjusted range. On the other hand, it was more tractable mathematically, an Messrs Lloyd and Anis had been able to obtain its exact value for any finite number o normal increments. Previous figures for the range (both adjusted and otherwise) we asymptotic values, valid only for large N. It was of interest, however, that the exac expected value of the non-adjusted range also behaved like $N^{\frac{1}{2}}$ for large N.

One of the most challenging of the Author's findings was his empirical law, valid ove an astonishingly wide range of phenomena, that the range in reality behaved somethin

like $N^{\frac{3}{4}}$ rather than $N^{\frac{1}{2}}$. It might be thought that a possible explanation of that discrepancy between theory and observation might lie in the nature of the distribution of the individual increments, in particular their non-normality. It was true that the Author's totalled frequencies showed an impressive agreement with the normal law, but that did not necessarily imply that the separate contributions were themselves normally distributed: if standardized frequencies from a sufficiently large number of sources were added, it was a general result that the totals would be closely normal, whatever (within wide limits) the nature of the contributing distributions. That line of enquiry, however, turned out to be fruitless, since Feller had shown that the $N^{\frac{1}{2}}$ law followed theoretically from the addition of independent increments even when they were non-normal.

A more promising line of investigation would probably be to attribute the $N^{\frac{3}{4}}$ result to lack of independence in the increments. That was a factor to which the Author had himself drawn attention. There the problem was to specify the form of the dependence; present indications were that that was likely to be quite complicated.

The Author, in reply, agreed with Mr Allan that an extension of his (the Author's) work was required to take account of losses in storage, which in some cases, such as the proposed large reservoir at Aswan, would be important. He agreed with Mr Allan that in arid climates, where there was no compensating rainfall, losses could be very important, and should be taken into account along with other special circumstances of the particular case. Mr Allan had also drawn attention to the possible effects of losses on policies as to regulation in arid countries in order to arrive at the most probable result.

The complexity of the problem and the uncertainties involved in using only the data from the past record of the river concerned could be seen by extending Mr Allan's example as followed. In Fig. 18 the accumulated departures of the annual discharge of the Nile at Aswan were plotted:—

(a) From 1899 to 1949 in the order in which they had occurred.
(b) By altering the order of occurrence so that the sequence was 1899–1915, 1939–49, 1916–38.
(c) For the sequence 1916–38, 1899–1915, 1939–49.

It would be seen that, giving in each case a draft equal to the average discharge and assuming no losses, would lead to the following three results:—

For (a), the content would have oscillated about the starting content with a range from 39 milliards above to 31 milliards below, or a total range of 70 milliards.

For (b), the content would have been well below the starting content for most of the time and would have ranged from 31 milliards above to 94 milliards below, a range of 125 milliards.

For (c), the content would have been above the starting content for most of the time, ranging from 101 milliards above to 25 milliards below, a range of 126 milliards.

In those three cases there would be different losses, with the highest in (c) and the lowest in (b), with the effect that the curves of content would be lowered by progressive amounts, the greatest lowering being on (c) and the smallest on (b). To form some idea of the respective probabilities of the arrangements K had been calculated for each, giving the following values: (a) 0·53; (b) and (c) 0·71. Since the mean of 729 values of K was 0·73, then (b) and (c) could not be ruled out as improbable, and it was clear that a wide range of losses was possible.

It was evident from the above example that losses calculated on the past record of a single phenomenon could be very misleading, and the only possibility was to deal statistically with the problem.

In any particular case, as for example the Nile at Aswan, it would be necessary to make a Table relating loss to content, and then, having chosen the suitable type of regulation, to apply the regulation and losses to a representative sample of phenomena, in the same way as in the Paper. That would involve a lot of labour, and a study would be made to

see if some of the computation could be avoided by inference from the previous statistical work. In that connexion, Papers by Professor Moran might give some clues.[13]

The Author was pleased that Mr Hunter's remarks confirmed his own views, and to learn that the Thames could rival the Nile in the changing of its mean discharge. The facts given by Mr Hawes about the equatorial lakes of the Nile Basin were interesting,

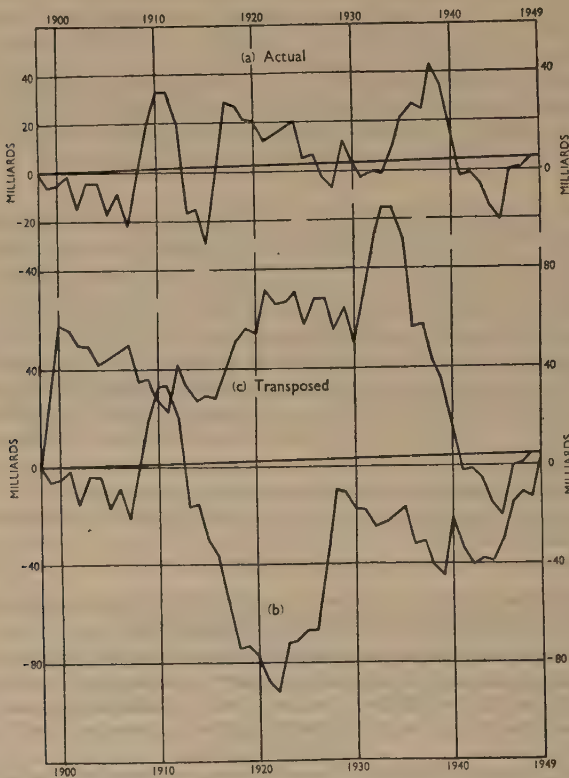

FIG. 18.—ASWAN DISCHARGE. ACCUMULATED DEPARTURES

for it was the importance of regulating them which had led the Author to start his invest gations on long-term storage.

He thanked Mr Gold for drawing attention to the persistence formula, and for th example which showed that the distribution of dry or wet days departed from a randor one. He did not agree with Mr Gold's procedure of eliminating R/σ from the two equa tions, one of which gave R for random events and the other for the sample of natur phenomena which had been examined. As Mr Gold had remarked, those two values wer not the same, and it was not strictly justifiable to eliminate R/σ, though it might b interesting to see the result of doing so. The Author's earlier Paper,[1] which had probabl not been available to all the contributors, had given some description of K, and ha

[13] References 13 *et seq.* are given on p. 576.

shown that it had a normal distribution about a mean value of 0·73 with a standard deviation of 0·09 for 690 values. The following figures showed average values of K taken from the 4,000 years' record of varves in Lake Saki in the Crimea.

Length of sample: years	50	100	200	500	1,000
Number of samples	40	40	20	8	4
Mean value of K	0·70	0·60	0·70	0·69	0·78

Although K was not a constant its distribution was a stable one.

Mr Rowntree had asked if there was any indication of a number of cyclic variations causing irregularity. So far as the Author had been able to find out such periodicities as had been found in meteorological phenomena had been of small amplitude and negligible compared with the irregular variations. For example the old records of the Roda (Cairo) Nilometer had been analysed and periods had been found ranging from 2 to 240 years. None of the periods, however, was pronounced enough to be discoverable except by refined analysis, the amplitudes being of the order of 10 cm. The most pronounced had an amplitude of 17 cm, so that the difference between a high flood and a low one, if it depended only on the periodicity, would be about one-third of a metre. For comparison one might note that in the period 1870 to 1900 the highest and lowest floods occurred in successive years, and the difference between them was $2\frac{3}{4}$ m. The only phenomenon known to the Author which showed a regular and well-marked periodicity was sunspot-numbers, and Brookes and Carruthers[11] had remarked: "The literature of meteorology abounds with periodicities, many of which are of very doubtful value".

With regard to calendar years or water years, the first had been used throughout, since the data was published in that form and, though the second was desirable, the labour of computing means for several thousand years would have been prohibitive.

The Author agreed with Mr Thompson that the rounded formulae given by him were good enough for practical purposes. Actually the usual practice had been followed in giving K to two digits, since the probable error of the mean value of K from 690 examples was 0·006 so that the mean value of K might have been given as $0{\cdot}729 \pm 0{\cdot}006$. (The value 0·72 had been adopted in order to give greater weight to the more precise measurements relating to rivers, rainfall, and temperature.)

With regard to the comments of Mr Sharman and Mr Cochrane, the Author thought they could not have studied his original Paper[1] very closely, or they would not have suggested that he had narrowly escaped "limbo" to run his head into a "cul-de-sac", and admonished him to abjure his "statistical heresies". That predicament would now be examined to see if it was serious as it might appear superficially.

Mr Sharman had written that the evidence for the statistical similarity of river discharges, rainfall, and temperature was rather scanty and referred to the frequency distributions of Fig. 2 in which only 169 observations were actual river discharges out of nearly 6,000, which included river and lake levels, rainfall, and temperatures. "Run-off was a totally different kind of end-product" from those. Nevertheless, the frequency distributions of run-off and the other phenomena were similar. That was shown by the curve of Fig. 19 which depended on nearly 2,000 observations of discharges of thirty-three rivers in Africa, America, Australia, England, and India. It would be seen that the distribution approximated closely to the Gaussian. The average length of a record was 60 years.

That similarity of distribution, in which order of occurrence was not considered, had been originally thought by the Author to be an important factor in determining R. It had been recently shown,[14] however, that when N was large, the range R was independent of the form of the distribution. It was clear also from the Author's data that the variations of K were mainly due to the order of occurrence or grouping of the variates.

The main part of the Author's first Paper[1] was the investigation of the properties of R, on which the size of a long-term storage reservoir would have to depend, and that resulted in equations (1) and (2).

The form of equation (1) depended on phenomena with long records, and the striking

fact was not "that the only thing the phenomena had in common was their anarchy", but the stability of the stochastic quantity K. That was shown in Table 13, in which additional data about river discharges had been added, and discharges had been separated from levels.

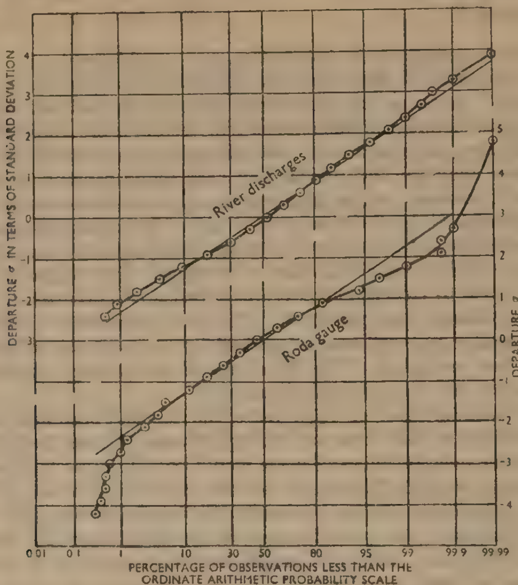

FIG. 19.—FREQUENCY DISTRIBUTIONS OF ANNUAL VALUES OF DISCHARGES OF THIRTY-THREE RIVERS (1938 OBSERVATIONS) AND OF RODA GAUGE READINGS (797 OBSERVATIONS)

TABLE 13.—VALUES OF K

Phenomena	Number of values	Mean	Standard deviation	Standard deviation of mean
River discharges	41	0·72	0·03	0·005
Lake or river levels . . .	112	0·76	0·06	0·006
Rainfall	168	0·70	0·07	0·005
Temperature and pressure .	115	0·70	0·08	0·007
Annual growth of tree rings	85	0·80	0·08	0·009
Varves, Crimea	114	0·69	0·06	0·006
Varves, Canada and Norway	90	0·77	0·09	0·009
Means	725	0·73	0·08	0·003

The values of K had an approximately Gaussian distribution as shown in Fig. 20. Table 13 showed conclusively the similarity with regard to K, and therefore to R, of the phenomena in the Table. Moreover mean K for river discharges was practically the same as the mean of all values.

A further proof of similarity was shown by the computations of S, the maximum deficit nen the draft was less than the mean, summed up in equations (2), and shown in Fig. 8 the first Paper.[1]

Mr Cochrane had stated: "In the introduction the Author said that things were not ndom, but in the Paper he went on to say that the data were distributed in a Gaussian anner". Actually the Author had said, more than once, "Although many natural

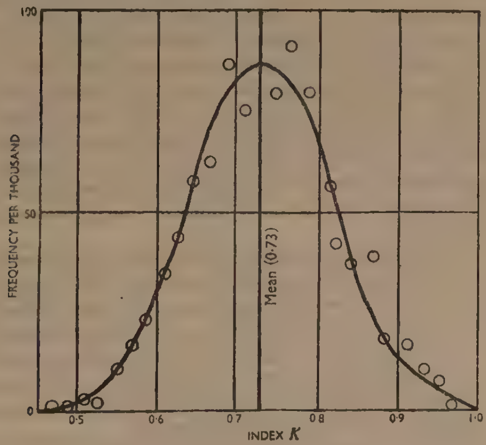

FIG. 20.—FREQUENCY OF INDEX K (690 VALUES)

nenomena have a nearly normal frequency distribution, this is only the case when their rder of occurrence is ignored".

"Random" was used by the Author with its mathematical meaning, that one event was dependent of its predecessors, as in tossing pennies or throwing dice. It might, however, be mentioned that events could be random without the distribution being Gaussian. uch a case was the distribution of shots on a target in relation to their distance from the ntre of the bull's eye. The Author's intention had been to examine and describe the atistical properties of R, as related to those of natural phenomena, and not to attempt e colossal work, which had occupied meteorologists for the past century, of finding a nysical explanation of them. As a description, the statement that high values tended group together and low values also, seemed to be much more accurate than to talk oout cycles, which had not a very definite meaning, though it usually implied definite eriodicities, which, however, in the phenomena examined by the Author, did not exist. hat could easily be seen by a glance at the Figures in the Paper. On that point Professor M. G. Kendall might be quoted.[15] "Enthusiasts have claimed to discover cyclical ovements in almost every phenomenon for which records are available over a long eriod. More sober study has tended to reject the majority of these claims".

With regard to the minor points raised by Mr Cochrane, the precipitation at Stockholm as 20–25% snow. The levels at Roda were related to the discharge of the Nile, and, oough the relation was neither an exact nor a linear one, it was near enough to produce milar frequency curves. As to the manufacture of varves, it would seem to be quite ossible to make them with a constant thickness, or with a thickness varying in any efined manner. However, since so far it was not possible to describe the succession of arves in nature by a mathematical function, it would not be possible to produce natural

sequences, except copies of what had already occurred. In any case the matter was n
relevant to the use of varves in the original Paper.[1]

The Author agreed with Mr Wolf on the value of statistical methods as a means o
research and would point out that statistical methods were the tools of the great maste
of mathematical physics, and were the very foundations of several branches of physic
beginning with the kinetic theory of gases, and continuing with quantum theory an
atomic physics in modern times. Mr Wolf's suggestion of the necessity of more work o
the subject was very sound. It would be very valuable if more phenomena could be foun
for which long-period records existed. In that connexion the figures given by Professo
M. Laushey in the discussion on the first Paper[1] were interesting. They related t
fluctuations of the squares of the velocity in a turbulent stream, for which a mean valu
of K was about 0·66, depending on 300 measurements which occupied one minute. It wa
possible that other data existed on what one might call a micro-time scale, and woul
yield interesting results. Analysis of a quantity of data would need computation on a
large scale and the Author was glad that Mr Wolf and Professor Barnard agreed that tha
could profitably be done by machines of the types recently developed.

The Author was grateful to Professor Barnard for information about work on stock
piling, queues, and Dr Jowett's variogram, of which he was ignorant, and for references t
the literature on the subject.

Mr David Lloyd's example from Liverpool waterworks practice was interesting, for i
agreed approximately with the results of the formulae. With regard to variation of a
phenomenon within a year, that had not been included in the Author's work, because i
the case of the Nile it had been well understood and of a fairly regular nature, so that i
dealing with projects a typical annual regulation could be superposed on the regulatio
to deal with the variation from year to year, and the long-term storage increased to cove
annual operation. It might be that, with a seasonal variation of less regular features tha
that of the Nile, regulation would be more complicated.

Mr Black had emphasized and put clearly some of the principal conclusions to be draw
from the work. He had also mentioned a difficulty, which could well arise in arid countrie
whose main source of life was water of a river, in the conflict of interests between industr
and agriculture, the one in maintaining high levels for power and the other in using a wid
range of levels so as to get maximum crops from the available water.

Mr Black and Mr Naguib Boulos had stated that in a reservoir problem it was bette
to use the mean values of K than the value obtained from the records of the flow to b
stored, and Mr Boulos had computed the results of both procedures and so justified th
statement. That was the "acid test" mentioned by Mr Sharman, and the result con
firmed the Author's views.

Mr Thomas had asked some questions of general interest. It was possible to answe
some of them but, as Mr Thomas had remarked, others would require a considerabl
amount of computation. Considering frequency distributions, Table 2 showed that th
distributions of the phenomena used by the Author approximated to the normal whe
the order of occurrence was ignored. A rough analysis showed that in 24 cases Pearson
measure of skewness—mean mode ÷ standard deviation—was positive; in 22 case
negative; in 4 cases zero; and in one case uncertain. The mean values of skewness fo
groups were:

Rainfall	0·09
River discharges and levels	− 0·23
Temperature	− 0·04

The second group consisted mainly of Roda gauge readings. It would be seen that o
the whole the skewness was small. No very small rainfall was included in the samp
thus avoiding cases which were likely to be considerably skew. With regard to the typ
of data mentioned by Mr Thomas all were mean annual values, except Roda gau
readings, which were maxima.

Next, K had been compared with skewness. For the cases of positive skewness the mean value of K was 0·74 and for the negative cases 0·73. If skewness was taken ignoring its sign, the mean for $K < 0·73$ was 0·26 and for $K > 0·74$ it was 0·32. It was clear from that that the effect on K of the small degree of skewness in the data was negligible, thus agreeing with Feller's conclusion,[14] and removing any doubts as to the validity of the Author's equations over a wide range.

With regard to persistence the most important phenomenon was not a year-to-year correlation due to some cause which gradually died down, but rather a persistence over an indefinite period of something which caused values on the whole to be, for example, high and then changing in the course of a year or two to the opposite. Fig. 1, New York rainfall, illustrated that. From 1830 to about 1856 values were on the whole below the 120-year average, then until about 1904 above it, until 1931 below it, and then again above. The value of K for the whole period in that case was 0·74. The same characteristic was shown in other Figures in the Paper. A similar distribution was indicated by the other figures. In the extreme case of Aswan discharge, one year was correlated with the next for the period 1870–1952 and showed a coefficient 0·55 ± 0·05. Fig. 5 showed the sudden change of mean value after 1898, the values of r were 0·11 for the first period, and 0·12 for the second, neither of which was significant. The correlation for the whole period was therefore very largely due to the effect of the sudden change.

The Author agreed with Mr Thomas that a reasonable physical explanation of a phenomenon, when one could be found, was very valuable support for a conclusion based on statistics, and could help in the discarding of results due only to coincidence.

As to Roda gauge readings, they related to the Middle Ages when all of Upper Egypt and much of Lower Egypt had been under basin irrigation and the river had been uncontrolled. In a high flood the country had been completely covered right to the desert edge, and in a low flood a good deal of land would not be watered. The effect of that would be a kind of reduction of floods on a sliding scale, but would not alter their sequence, and so would probably have little effect on K. As to changes in the gauge-discharge relation due to changes of river-bed in the Delta, similar changes took place on any river flowing in alluvium, and should be taken as part of the general variation. Actually the effect of them was smaller in flood than in low stage.

Several contributors had mentioned the extremes of the frequency curves of Fig. 2. The method of plotting the curve was explained by the legend attached. The lowest group in the Table, for example, was departures $-4·5\sigma$ to $-4·21\sigma$, and that included all departures greater than $-4·21\sigma$, for there were none greater than 4·5, and its frequency was 0·3 per thousand. Reference to Table 2 showed that below $-3·6\sigma$ there were only four observations, whilst above $3·9\sigma$ there were only three observations. That seemed far too small a sample on which to base any conclusions as to the form of the curve at its limits. Incidentally the four lowest observations were for Roda gauge, and the three highest were one each for Roda, temperature, and rainfall. (A frequency curve for Roda gauge was included in Fig. 19.)

Extreme high floods were affected by the Nile overflowing its banks in the Northern Sudan, from which a considerable quantity of water did not return, a fact which had first been discovered in the high flood of 1946.

Dr E. H. Lloyd and Dr Anis had explained the results obtained by Professor Feller, and referred to their own extensions of his work.[16, 17, 18] Their remarks would help to explain some of the difficulties raised by other contributors.

Mr Langbein had agreed with the Author and other contributors that neither skewness nor the persistence represented by serial correlation could account for the difference between natural and random phenomena in respect of R. He had also discussed the variation of the standard deviation with the length of period for a number of American rivers, and had derived a formula for it. The formula was correct if S_n, the standard deviation about a mean of n data, was the mean of the separate groups of n observations which together added up to the total N. He had taken as his data records of river flow for about 80 years and from a mean curve drawn through them had computed corrections

to be applied to the standard deviation for a short period of years to allow for the fac that the standard deviation of many natural phenomena increased with the length of th record. Mr Langbein's corrections were somewhat smaller than those given in th Author's Fig. 3. In Fig. 3 the lowest value of N_1 was about 30 years, and the highes value of N_2 more than 1,000. The data were fairly concordant up to $N_2/N = 20$. M Langbein had $N_1 = 2$ and N_2 a maximum of 75. That was to say, nearly all his data la below the range covered by Fig. 3, and the difference between the results was probabl due to that. The Author was a little doubtful whether, for example, the ratio betwee standard deviations of such small periods as 15 and 5 years could legitimately be com pared with the case of 90 and 30 years. The increase of standard deviation was un doubtedly largely due to grouping, and as Mr Langbein had implied, that would have les effect on small samples.

In conclusion, the Author would like to thank the Institution for giving him the oppor tunity to make that work known which had been done in connexion with his professiona duties for the Egyptian Government. He also thanked the contributors to the discussio for many valuable suggestions. He was grateful to Mr Allard for drawing his attentio to important work done in Australia,[20] and Mr Langbein for supplying him with data fo some American rivers, and for allowing him to see the manuscript of a forthcomin Paper on "Variations in annual streamflow and their effects on water supply and storage"

Table 14 on the following pages gave a summary of the basic data which had been use by the Author, for the assistance of others who might wish to work on the subject.

Some additional Papers bearing on the subject were given under the heading Furthe References.

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TABLE 14.—DATA ADDITIONAL TO TABLE 3

R = range of Accumulated Departures from the mean
σ = Standard Deviation M = mean
N = number of years $K = \log (R/\sigma)/\log (N/2)$

Station and phenomenon	Period	N	M	σ	R	K
1. *River discharges*						
ampaspe, Australia	1886–1945	60	1·8	1·4	13	0·65
edar, U.S.A.	1896–1950	55	69	15	190	0·78
odavari, India	1881–1936	55	36	12	150	0·76
oulburn, Australia	1882–1945	64	2·2	1·0	10	0·66
ake Huron	1860–1948	89	188	20	720	0·94
istna, India	1881–1936	56	234	100	1,500	0·80
errimack, U.S.A.	1880–1945	66	70	16	210	0·74
ississippi, U.S.A.	1874–1936	63	48	13	190	0·77
ile, Aswan, Egypt	1871–1908	38	104	17	200	0·93
	1909–1945	37	82	14	83	0·60
	1871–1945	75	94	18	480	0·90
ile, Atbara, Sudan	1903–1936	34	125	41	210	0·58
ile, Sobat, Sudan	1905–1936	32	139	28	190	0·69
ile, L. Albert, Uganda	1904–1944	41	23	7·2	77	0·78
ile, L. Victoria	1896–1944	49	21	4·8	40	0·66
ripet, U.S.S.R.	1882–1917	36	122	34	210	0·64
ripet and Dnieper, U.S.S.R.	1878–1924	47	132	28	200	0·61
hine, Germany	1881–1930	50	1,040	200	1,960	0·71
pokane, U.S.A.	1892–1950	59	6·7	2·0	25	0·75
udbury, U.S.A.	1876–1945	70	20	6·1	78	0·72
ennessee, U.S.A.	1875–1935	61	38	9	67	0·60
hames	1883–1953	71	144	46	730	0·77
ruckee, U.S.A.	1839–1871	33	107	98	580	0·64
	1872–1904	33	107	59	320	0·60
	1905–1938	34	87	52	500	0·80
	1839–1904	66	107	81	580	0·57
	1872–1938	67	97	57	760	0·74
	1839–1938	100	100	73	1,110	0·69
ischarges, percentage of median						
razos, U.S.A.	1899–1952	54	124	81	720	0·66
hattanoochee, U.S.A.	1896–1952	57	104	31	260	0·63
olorado, U.S.A.	1896–1952	57	101	28	410	0·80
olumbia, U.S.A.	1896–1952	57	99	19	290	0·82
ings, U.S.A.	1896–1952	57	104	45	470	0·69
ississippi (Keokuk), U.S.A.	1896–1952	57	104	29	370	0·77
issouri, U.S.A.	1896–1952	57	100	28	460	0·84
iagara, U.S.A.	1896–1952	57	101	7	110	0·81
emigewasset, U.S.A.	1896–1952	57	100	16	180	0·72
ed, U.S.W.	1896–1952	57	126	83	1,530	0·87
io Grande, U.S.A.	1896–1952	57	96	30	440	0·80
acramento, U.S.A.	1896–1952	57	106	42	610	0·79
usquehanna, U.S.A.	1896–1952	57	102	20	190	0·68
					41 cases; mean	0·73
2. *Lake and river levels*						
ake on Dalalven River, Sweden	1765–1808	44	209	33	430	0·84
	1809–1852	44	192	28	210	0·65
	1853–1896	44	182	26	160	0·59
	1897–1940	44	186	26	240	0·71
	1765–1852	88	200	32	600	0·78
	1809–1896	88	187	28	310	0·64
	1853–1940	88	184	26	360	0·69

TABLE 14.—*continued*

Station and phenomenon	Period	N	M	σ	R	K
2. *Lake and river levels—continued*						
	1765–1896	132	194	31	740	0·76
	1809–1940	132	187	27	330	0·59
	1765–1940	176	192	30	840	0·75
Rhine, Germany	1881–1930	50	247	32	310	0·85
Lake Runn, Sweden . . .	1852–1938	87	17	2·1	27	0·67
Lake Vattern, Sweden	1858–1939	82	49	14	160	0·66
			13 cases; mean 0·71			
Roda gauge, Egypt	1867–1946	80		0·86	14	0·75
	641–740	100		0·72	10	0·68
	741–840	100		0·61	8	0·65
	841–940	100		0·51	9	0·74
	941–1041	100		0·38	5	0·65
	1042–1142	100		0·44	11	0·82
	1143–1242	100		0·48	14	0·86
	1243–1344	100		0·44	7	0·72
	1345–1445	100		0·66	14	0·78
	1446–1741	100		0·73	11	0·69
	1742–1866	100		0·69	18	0·84
	1742–1946	180		0·77	22	0·74
	641–840	200		0·68	17	0·70
	741–940	200		0·57	8	0·58
	841–1041	200		0·48	16	0·76
	941–1142	200		0·45	16	0·78
	1042–1242	200		0·47	20	0·82
	1143–1344	200		0·46	15	0·76
	1243–1445	200		0·65	34	0·86
	1345–1741	200		0·74	40	0·86
	1446–1886	200		0·72	21	0·74
	1446–1946	280		0·76	32	0·75
	741–1041	300		0·53	20	0·72
	641–940	300		0·63	21	0·70
	841–1142	300		0·47	24	0·78
	941–1242	300		0·45	29	0·83
	1042–1344	300		0·47	24	0·78
	1143–1445	300		0·61	46	0·86
	1243–1741	300		0·68	42	0·82
	1345–1866	300		0·72	43	0·82
	1345–1946	380		0·76	40	0·76
	641–1041	400		0·60	31	0·74
	741–1142	400		0·52	26	0·74
	841–1242	400		0·51	24	0·72
	941–1334	400		0·45	30	0·80
	1042–1445	400		0·58	47	0·83
	1143–1741	400		0·65	46	0·81
	1242–1866	400		0·69	40	0·77
	1243–1946	480		0·72	41	0·74
	641–1142	500		0·58	30	0·72
	741–1242	500		0·51	22	0·68
	841–1344	500		0·47	26	0·72
	941–1445	500		0·56	50	0·81
	1042–1741	500		0·61	46	0·78
	1143–1866	500		0·66	49	0·78
	1143–1946	580		0·69	58	0·79
	641–1242	600		0·56	34	0·72

TABLE 14—*continued*

Station and phenomenon	Period	*N*	*M*	σ	*R*	*K*
2. *Lake and river levels—continued*						
Roda gauge, Egypt—*continued*	741–1344	600		0·50	24	0·68
	841–1445	600		0·55	57	0·81
	941–1741	600		0·59	59	0·81
	1042–1866	600		0·63	52	0·78
	1042–1946	680		0·66	62	0·78
	641–1344	700		0·54	40	0·74
	741–1445	700		0·56	56	0·79
	841–1741	700		0·58	64	0·80
	941–1866	700		0·61	68	0·81
	941–1946	780		0·64	80	0·78
	641–1445	800		0·59	74	0·81
	741–1741	800		0·58	64	0·78
	841–1866	800		0·60	74	0·80
	841–1946	880		0·63	80	0·80
	641–1741	900		0·61	78	0·80
	741–1866	900		0·60	76	0·79
	741–1946	980		0·63	83	0·79
	641–1866	1000		0·69	86	0·78
	641–1946	1080		0·64	88	0·78
					99 cases; mean	0·75
3. *Rainfall*						
Accra, Africa	1888–1920	32	27	8	53	0·68
Freetown, Africa	1875–1920	46	160	29	440	0·87
Karlsbad, Czechoslovakia	1860–1944	83	60	13	160	0·68
Haparanda-Tanersburg, Sweden	1860–1944	85	72	13	170	0·69
Helsingfors, Finland	1903–1930	28	680	88	520	0·67
	1845–1873	29	550	110	600	0·64
	1874–1902	29	640	110	560	0·60
	1874–1930	57	660	100	880	0·64
	1845–1902	58	600	120	1,630	0·78
	1845–1930	86	630	120	2,500	0·82
Greenwich, U.K.	1841–1870	30	610	120	530	0·55
	1871–1900	30	600	83	780	0·82
	1901–1930	30	630	110	500	0·57
	1841–1900	60	610	100	720	0·59
	1871–1930	60	620	98	1,070	0·70
	1841–1930	90	620	100	1,060	0·61
Washington, U.S.A.	1824–1869	30	38	8·7	64	0·73
	1870–1899	30	43	8·2	71	0·80
	1900–1930	31	40	5·9	39	0·69
	1824–1899	60	40	8·8	140	0·81
	1870–1930	61	42	7·2	89	0·74
	1824–1930	91	40	8·0	150	0·77
Sydney, Australia	1890–1930	41	46	10	77	0·66
	1840–1899	50	49	14	91	0·58
	1840–1930	91	48	12	140	0·63
Adelaide, Australia	1839–1884	46	21	4·1	35	0·68
	1885–1930	46	21	4·6	32	0·62
	1839–1930	92	21	4·4	38	0·57
Cape Town, S. Africa	1838–1868	30	24	4·4	32	0·73
	1869–1899	31	27	5·9	34	0·64
	1900–1930	31	24	4·3	34	0·76
	1838–1899	61	25	5·5	74	0·76
	1869–1930	62	25	5·5	79	0·78
	1838–1930	92	25	5·2	100	0·78

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
3. *Rainfall—continued*						
St. Louis, U.S.A.	1837–1867	31	43	9·4	80	0·78
	1868–1898	31	38	6·8	34	0·59
	1899–1930	32	37	6·6	41	0·67
	1837–1898	62	41	8·6	120	0·76
	1868–1930	63	38	6·7	42	0·53
	1837–1930	94	40	8·2	150	0·76
St. Paul, U.S.A.	1837–1883	47	28	6·2	65	0·74
	1884–1930	47	27	5·4	61	0·77
	1837–1930	94	27	5·9	92	0·71
Frankfort, Germany	1837–1883	47	64	14	89	0·59
	1884–1930	47	60	10	110	0·74
	1837–1930	94	62	12	190	0·71
Bangalore, India	1886–1930	45	34	7·1	48	0·58
	1835–1885	50	36	8·2	36	0·46
	1835–1930	95	35	7·8	54	0·50
Portsmouth, U.K.	1830–1881	49	40	7·2	55	0·63
	1882–1930	49	42	6·4	47	0·62
	1830–1930	98	41	6·9	86	0·65
Calcutta, India	1829–1879	50	66	11	120	0·74
	1880–1930	51	63	11	80	0·60
	1829–1930	101	64	12	160	0·68
Trier	1896–1930	35	730	120	1,050	0·77
	1860–1895	36	680	100	640	0·62
	1806–1859	36	660	120	1,120	0·78
	1860–1930	71	700	110	1,380	0·69
	1806–1895	72	670	110	1,220	0·67
	1806–1930	107	690	120	1,990	0·71
Charleston, U.S.A.	1882–1930	49	44	9·3	140	0·85
	1832–1881	50	50	12	170	0·83
	1832–1930	99	47	11	290	0·84
	1832–1945	114	47	11	290	0·82
Copenhagen, Denmark . . .	1876–1930	55	58	7·7	72	0·67
	1821–1875	55	57	11	76	0·59
	1821–1930	110	58	9·4	140	0·67
	1821–1938	118	58	9·3	140	0·67
New York, U.S.A.	1896–1930	35	41	4·3	41	0·79
	1861–1895	35	45	6·1	41	0·67
	1826–1860	35	40	7·0	64	0·77
	1861–1930	70	43	5·7	92	0·79
	1826–1895	70	42	7·1	130	0·82
	1826–1930	105	42	6·3	140	0·79
	1826–1945	120	42	6·3	130	0·74
Albany, U.S.A.	1826–1860	35	40	5·3	38	0·69
	1861–1895	35	39	6·0	46	0·71
	1896–1930	35	32	4·2	26	0·64
	1826–1895	70	40	5·7	52	0·62
	1861–1930	70	36	6·1	120	0·84
	1826–1930	105	37	6·2	180	0·72
	1826–1945	120	37	6·0	200	0·85
Philadelphia, U.S.A. . . .	1904–1945	42	41	5·6	37	0·62
	1862–1903	42	43	7·0	100	0·88
	1820–1861	42	43	6·2	47	0·67
	1862–1945	84	42	6·3	100	0·75
	1820–1903	84	43	6·6	130	0·80
	1820–1945	126	42	6·3	150	0·76

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
3. *Rainfall—continued*						
Boston, U.S.A.	1904–1945	42	38	5·0	52	0·77
	1861–1903	43	44	7·0	72	0·76
	1818–1860	43	43	7·4	68	0·73
	1861–1945	85	41	6·9	180	0·87
	1818–1903	86	44	7·1	140	0·80
	1818–1945	128	42	7·0	220	0·83
Madras, India	1813–1856	44	49	16	110	0·64
	1857–1900	44	48	15	130	0·69
	1901–1945	45	51	14	93	0·60
	1813–1900	88	49	15	120	0·54
	1857–1945	89	50	15	110	0·52
	1813–1945	133	50	15	150	0·55
Rome, Italy	1782–1831	50	830	16	140	0·68
	1832–1881	50	780	16	160	0·72
	1882–1932	51	890	17	180	0·72
	1782–1881	100	800	16	280	0·72
	1832–1932	101	830	18	390	0·79
	1782–1932	151	830	17	400	0·71
Stockholm, Sweden	1785–1824	40	52	14	160	0·84
	1825–1864	40	38	7·8	70	0·73
	1865–1904	40	47	9·2	90	0·76
	1905–1946	41	58	8·8	80	0·73
	1785–1864	80	45	19	340	0·78
	1825–1904	80	43	15	210	0·73
	1865–1946	81	53	15	240	0·75
	1785–1904	120	46	12	420	0·88
	1825–1946	121	48	12	490	0·91
	1785–1946	161	49	12	660	0·91
Padua, Italy	1893–1934	42	820	170	1,850	0·77
	1850–1892	43	840	150	900	0·59
	1807–1849	43	790	160	1,750	0·78
	1764–1806	43	940	180	2,170	0·81
	1850–1934	85	830	160	1,550	0·60
	1764–1849	86	870	190	3,900	0·80
	1807–1934	128	820	170	3,000	0·70
	1764–1892	129	860	180	4,200	0·76
	1764–1934	171	850	180	4,500	0·73
Milan, Italy	1764–1789	24	91	14	75	0·68
	1790–1813	24	99	15	58	0·55
	1814–1837	24	100	19	90	0·63
	1838–1861	24	100	21	140	0·77
	1862–1886	25	100	21	120	0·69
	1887–1911	25	100	18	75	0·57
	1912–1936	25	96	20	140	0·77
	1764–1813	48	95	15	140	0·71
	1790–1837	48	100	17	120	0·61
	1814–1861	48	100	20	220	0·75
	1838–1886	49	100	21	220	0·75
	1862–1911	50	100	20	140	0·62
	1887–1936	50	100	19	200	0·74
	1764–1837	72	97	19	180	0·62
	1790–1861	72	100	19	250	0·72
	1814–1886	73	100	20	240	0·69
	1838–1911	74	100	20	230	0·68
	1862–1936	75	100	20	240	0·69
	1764–1861	96	100	18	340	0·76

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
3. *Rainfall—continued*						
Milan, Italy—*continued*	1790–1886	97	100	19	260	0·66
	1814–1911	98	100	20	230	0·63
	1838–1936	99	100	20	260	0·65
	1764–1886	121	100	19	340	0·70
	1790–1911	122	100	19	240	0·62
	1814–1936	123	100	20	270	0·63
	1764–1911	146	100	350	340	0·68
	1790–1936	147	100	370	280	0·63
	1764–1936	171	100	19	440	0·71
Zwanenburg, Holland . . .	1894–1945	52	74	11	72	0·57
	1841–1839	53	77	13	120	0·67
	1788–1840	53	69	11	130	0·77
	1735–1787	53	76	13	130	0·70
	1841–1945	105	76	12	140	0·60
	1735–1840	106	73	12	240	0·74
	1788–1945	158	74	12	280	0·72
	1735–1893	159	74	13	270	0·70
	1735–1945	211	74	12·4	280	0·66
				163 cases; mean		0·70
4. *Temperatures*						
Adelaide, Australia	1857–1924	68	63	0·89	11	0·72
Greenwich, U.K.	1841–1885	45	50	1·1	8·2	0·64
	1886–1930	45	50	1·0	9·6	0·74
	1841–1930	90	50	1·0	13	0·67
St. Louis, U.S.A.	1900–1930	31	56	1·4	7·6	0·62
	1836–1867	32	55	1·2	6·8	0·62
	1868–1899	32	56	1·3	6·4	0·58
	1868–1930	63	56	1·3	15	0·69
	1836–1899	64	55	1·3	12	0·65
	1836–1930	95	56	1·4	24	0·64
Washington, U.S.A.	1820–1866	32	54	1·6	14	0·80
	1867–1898	32	55	1·1	6·6	0·64
	1899–1930	32	55	1·3	9·2	0·72
	1820–1898	64	54	1·4	18	0·73
	1867–1930	64	55	1·2	12	0·67
	1820–1930	96	55	1·4	25	0·74
Helsingfors, Finland	1829–1862	34	4·0	0·86	3·9	0·54
	1863–1896	34	4·2	1·1	7·1	0·65
	1897–1930	34	4·7	0·87	3·6	0·50
	1829–1896	68	4·1	1·0	7·4	0·57
	1863–1930	68	4·4	1·0	11	0·68
	1829–1930	102	4·3	1·0	18	0·74
	1829–1940	102	4·4	1·1	26	0·78
Vienna, Austria	1825–1938	114	9·3	0·53	14	0·80
Rome, Italy	1811–1850	39	16	0·70	5·1	0·67
	1851–1890	40	15	0·42	4·1	0·77
	1891–1930	40	15	0·32	5·0	0·92
	1811–1890	79	15	0·59	9·2	0·74
	1851–1930	80	15	0·38	6·1	0·76
	1811–1930	119	15	0·54	14	0·79
Albany, U.S.A.	1813–1857	40	48	1·4	12	0·74
	1860–1904	41	48	1·5	12	0·70
	1905–1945	41	48	1·4	14	0·76
	1813–1904	81	48	1·5	22	0·73
	1860–1945	82	48	1·4	24	0·75
	1813–1945	122	48	1·4	21	0·66

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
4. *Temperatures—continued*						
Charleston, U.S.A.	1823–1863	41	66	1·3	13	0·76
	1864–1904	41	66	1·0	8	0·69
	1905–1945	41	66	1·0	12	0·82
	1823–1904	82	66	1·2	22	0·78
	1864–1945	82	66	1·0	12	0·67
	1823–1945	123	66	1·1	28	0·77
Vilno, U.S.S.R.	1885–1937	45	6·4	0·81	5·6	0·62
	1781–1832	52	6·3	1·1	8·8	0·64
	1833–1884	52	6·5	1·0	4·8	0·49
	1833–1937	97	6·5	0·92	9·2	0·57
	1781–1884	104	6·4	1·1	14	0·65
	1781–1937	149	6·3	0·97	16	0·65
Copenhagen, Denmark	1768–1810	29	7·9	0·87	3·4	0·51
	1811–1853	43	7·5	0·98	10	0·77
	1854–1896	43	7·4	0·73	3·0	0·47
	1897–1940	44	8·1	0·74	6·4	0·70
	1768–1853	72	7·6	0·95	12	0·71
	1854–1940	87	7·8	0·80	19	0·84
	1768–1896	115	7·6	0·88	18	0·74
	1811–1940	130	7·7	0·87	24	0·80
	1768–1940	159	7·7	0·73	26	0·81
Newhaven	1781–1821	40	49	1·3	18	0·87
	1822–1862	41	49	1·3	11	0·71
	1863–1903	41	49	1·4	14	0·78
	1904–1945	42	50	1·3	13	0·84
	1781–1862	81	49	1·4	18	0·70
	1863–1945	83	50	1·5	30	0·81
	1781–1903	122	49	1·4	25	0·71
	1822–1945	124	50	1·5	44	0·83
	1781–1945	164	49	1·5	46	0·78
Paris, France	1764–1804	41	11	0·92	13	0·88
	1805–1845	41	11	0·83	6·0	0·66
	1846–1886	41	11	0·57	4·5	0·69
	1887–1930	44	10	0·61	5·8	0·73
	1764–1845	82	11	0·89	15	0·76
	1846–1930	85	10	0·64	12	0·79
	1764–1886	123	11	0·80	15	0·71
	1805–1930	126	10	0·70	14	0·73
	1764–1930	167	11	0·78	18	0·72
Berlin, Germany	1769–1810	42	8·9	0·96	9·9	0·77
	1811–1852	42	8·7	0·88	6·4	0·65
	1853–1895	43	9·1	0·81	5·2	0·61
	1896–1938	43	9·4	0·61	3·4	0·56
	1769–1852	84	8·8	0·92	12	0·69
	1853–1938	86	9·2	0·71	7·0	0·61
	1769–1895	127	8·9	0·90	18	0·76
	1811–1938	128	9·1	0·82	18	0·74
	1769–1938	170	9·0	0·87	25	0·76
Stockholm, Sweden	1899–1942	43	6·1	0·93	9·0	0·74
	1764–1808	45	5·7	0·99	9·0	0·71
	1809–1853	45	5·7	0·99	11	0·77
	1854–1898	45	5·6	0·95	8·0	0·68
	1854–1942	88	5·8	0·98	17	0·76
	1764–1853	90	5·7	0·99	10	0·62
	1809–1942	133	5·8	0·98	23	0·75
	1764–1898	135	5·7	0·98	14	0·64
	1764–1942	178	5·7	0·97	20	0·68

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
4. *Temperatures—continued*						
Zwanenburg, Holland . . .	1894–1945	52	9·1	0·53	3·7	0·59
	1735–1787	53	9·0	0·75	7·0	0·68
	1788–1840	53	8·8	0·81	8·0	0·70
	1841–1893	53	9·0	0·74	4·5	0·55
	1841–1945	105	9·1	0·65	4·6	0·49
	1735–1840	106	8·9	0·78	12	0·70
	1788–1945	158	9·0	0·71	12	0·65
	1735–1893	159	9·0	0·77	14	0·66
	1735–1945	211	9·0	0·72	16	0·66
				102 cases; mean 0·70		
5. *Atmospheric pressure*						
Adelaide, Australia	1857–1924	68	30	0·030	0·38	0·72
Cape Town, S. Africa . . .	1842–1870	29	30	0·014	0·082	0·66
	1871–1900	30	30	0·012	0·090	0·75
	1901–1930	30	30	0·012	0·067	0·63
	1842–1900	59	30	0·013	0·11	0·63
	1871–1930	60	30	0·012	0·088	0·58
	1842–1930	89	30	0·013	0·12	0·58
Madras, India	1902–1930	29	810	11	66	0·68
	1842–1871	30	820	14	94	0·70
	1872–1901	30	820	14	68	0·60
	1872–1930	59	820	13	160	0·75
	1842–1901	60	820	14	110	0·60
	1842–1930	89	820	13	200	0·69
				13 cases; mean 0·66		
6. *Annual growth of trees—thickness of rings*						
Meadow Valley, California, U.S.A. California pines . .	1620–1669	50	2·9	0·71	13	0·90
	1670–1719	50	3·0	0·38	5·0	0·80
	1720–1769	50	2·7	0·27	3·0	0·74
	1770–1819	50	3·1	0·67	12	0·91
	1820–1869	50	2·6	0·40	4·0	0·71
	1870–1919	50	2·2	0·48	7·5	0·85
	1620–1719	100	3·0	0·58	15	0·84
	1720–1819	100	2·9	0·55	18	0·89
	1820–1919	100	2·4	0·49	16	0·89
	1620–1819	200	2·9	0·56	19	0·77
	1720–1919	200	2·6	0·59	31	0·86
	1620–1919	300	2·8	0·61	52	0·89
				12 cases; mean 0·84		
Pike's Peak, U.S.A. Pines and Douglas firs	1570–1619	50	1·0	0·30	3·4	0·75
	1620–1669	50	0·90	0·38	6·5	0·88
	1670–1719	50	1·0	0·37	7·0	0·91
	1720–1769	50	0·83	0·27	1·1	0·64
	1770–1819	50	1·3	0·23	1·7	0·62
	1820–1869	50	0·99	0·19	2·4	0·79
	1870–1919	50	0·80	0·14	1·3	0·69
	1570–1669	100	0·95	0·35	7·2	0·77
	1670–1769	100	0·93	0·34	12	0·90
	1770–1869	100	1·2	0·26	9·3	0·91
	1820–1919	100	0·90	0·19	5·4	0·85
	1570–1769	200	0·94	0·34	11	0·76
	1670–1869	200	1·0	0·32	15	0·84
	1720–1919	200	0·98	0·29	19	0·91
	1570–1919	350	0·99	0·32	21	0·81
				15 cases; mean 0·80		

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
6. *Annual growth of trees—thickness of rings—continued*						
agstaff, Arizona, U.S.A. Pines	1400–1449	50	1·0	0·35	5·9	0·87
	1450–1499	50	0·87	0·27	2·5	0·69
	1500–1549	50	0·85	0·26	3·0	0·76
	1550–1599	50	1·2	0·34	4·4	0·79
	1600–1649	50	1·0	0·30	4·8	0·86
	1650–1699	50	0·95	0·25	3·5	0·82
	1700–1749	50	1·1	0·30	4·9	0·86
	1750–1799	50	0·92	0·25	3·6	0·83
	1800–1849	50	0·87	0·25	2·6	0·73
	1850–1899	50	1·0	0·35	6·7	0·92
	1400–1499	100	0·95	0·33	7·6	0·80
	1500–1599	100	1·0	0·34	8·6	0·82
	1600–1699	100	0·98	0·28	7·6	0·85
	1700–1799	100	1·9	0·29	7·2	0·82
	1800–1899	100	0·96	0·31	8·7	0·85
	1400–1599	200	0·98	0·33	17	0·85
	1500–1699	200	0·99	0·31	13	0·82
	1600–1799	200	0·99	0·29	9·6	0·76
	1700–1899	200	0·98	0·30	11	0·78
	1400–1899	500	0·98	0·31	18·2	0·74
					20 cases; mean	0·81
quoia, or Californian Redwood California, U.S.A.	1000–1049	50	1·25	0·20	3·8	0·91
	1050–1099	50	0·99	0·19	3·4	0·90
	1100–1149	50	0·98	0·13	1·7	0·79
	1150–1199	50	0·88	0·21	1·9	0·68
	1200–1249	50	0·84	0·11	1·5	0·82
	1250–1299	50	0·85	0·15	1·2	0·64
	1300–1349	50	1·13	0·13	0·8	0·56
	1350–1399	50	1·02	0·13	1·8	0·82
	1400–1499	50	0·88	0·15	2·5	0·88
	1450–1499	50	0·80	0·09	1·8	0·93
	1500–1549	50	0·92	0·14	1·0	0·61
	1550–1599	50	0·78	0·15	1·9	0·79
	1600–1649	50	0·88	0·11	1·2	0·74
	1650–1699	50	0·77	0·08	1·0	0·77
	1700–1749	50	0·83	0·14	2·3	0·86
	1750–1799	50	0·96	0·18	2·2	0·77
	1800–1849	50	0·88	0·13	1·9	0·84
	1850–1899	50	0·94	0·15	3·2	0·94
	1000–1099	100	1·12	0·23	7·0	0·87
	1100–1199	100	0·93	0·16	3·6	0·79
	1200–1299	100	0·86	0·14	2·2	0·71
	1300–1399	100	1·07	0·13	3·2	0·82
	1400–1499	100	0·84	0·13	3·7	0·85
	1500–1599	100	0·85	0·13	3·9	0·87
	1600–1699	100	0·83	0·12	2·9	0·81
	1700–1799	100	0·89	0·17	4·3	0·82
	1800–1899	100	0·91	0·15	4·5	0·87
	1000–1199	200	1·0	0·22	12	0·86
	1200–1399	200	0·97	0·18	12	0·91
	1400–1599	200	0·84	0·14	4·9	0·77
	1600–1799	200	0·86	0·15	7·6	0·86
	1700–1899	200	0·90	0·16	4·7	0·73
	1000–1299	300	0·97	0·21	17	0·87
	1300–1599	300	0·92	0·18	17	0·90

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
6. *Annual growth of trees—thickness of rings—continued*						
Sequoia, or Californian Redwood California, U.S.A.—*continued*	1600–1899	300	0·88	0·15	9·3	0·82
	1000–1499	500	0·96	0·20	18	0·81
	1400–1899	500	0·86	0·14	13	0·82
	1000–1899	900	0·93	0·18	34	0·86
				38 cases; mean		0·81
				85 cases of tree rings; mean		0·81
7. *Thickness of annual layers of mud, varves*						
Lake Saki, Crimea, U.S.S.R. .	B.C. 2090–A.D. 1889	50	16	7·9	65	0·65
		50	13	5·5	70	0·78
		50	14	6·9	100	0·83
		50	10	2·8	30	0·74
		50	14	7·1	60	0·66
		50	11	6·3	55	0·67
		50	11	4·6	45	0·71
		50	10	3·2	25	0·64
		50	10	3·2	30	0·69
		50	10	3·0	25	0·66
		50	14	7·0	85	0·77
		50	10	4·3	40	0·69
		50	14	15	105	0·61
		50	13	5·6	35	0·56
		50	14	6·6	60	0·68
		50	10	3·9	25	0·58
		50	12	4·4	35	0·64
		50	14	5·3	55	0·73
		50	11	4·8	45	0·69
		50	11	4·4	45	0·72
		50	13	7·1	65	0·68
		50	11	3·7	45	0·78
		50	16	12	85	0·60
		50	12	4·8	45	0·69
		50	11	4·0	45	0·75
		50	13	7·3	55	0·63
		50	12	4·9	50	0·72
		50	10	3·9	35	0·68
		50	12	4·1	35	0·66
		50	16	6·6	65	0·71
		50	14	6·3	80	0·78
		50	16	7·6	65	0·66
		50	20	12	120	0·70
		50	18	7·1	70	0·71
		50	13	5·6	45	0·64
		50	15	11	110	0·71
		50	15	7·8	105	0·81
		50	16	6·4	60	0·69
		50	14	6·5	100	0·86
		50	17	8·1	90	0·75
		100	16	7·2	65	0·56
		100	14	6·3	95	0·69
		100	13	7·1	120	0·69
		100	12	9·4	190	0·77
		100	12	6·3	140	0·78
		100	12	5·6	100	0·75
		100	10	4·7	55	0·63

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
7. *Thickness of annual layers of mud, varves—continued*						
Lake Saki, Crimea, U.S.S.R.—*continued*	B.C. 2090–A.D. 1889—*continued*	100	11	3·4	65	0·76
		100	11	5·2	80	0·70
		100	10	3·7	65	0·74
		100	12	6·7	120	0·73
		100	11	5·4	80	0·69
		100	14	12	200	0·73
		100	12	5·8	65	0·62
		100	13	5·5	110	0·76
		100	11	3·7	45	0·64
		100	12	4·0	45	0·62
		100	13	6·1	180	0·86
		100	12	5·8	100	0·72
		100	11	4·9	80	0·71
		100	14	6·2	70	0·62
		100	11	4·8	75	0·70
		100	14	9·7	140	0·69
		100	12	5·3	83	0·70
		100	11	4·8	63	0·65
		100	13	6·2	55	0·56
		100	12	4·8	62	0·65
		100	11	3·9	45	0·62
		100	16	21	280	0·65
		100	14	6·1	110	0·74
		100	14	5·3	100	0·75
		100	15	6·8	75	0·61
		100	21	11	170	0·70
		100	18	8·3	100	0·64
		100	14	5·8	90	0·70
		100	16	10	140	0·66
		100	15	7·4	110	0·69
		100	15	5·7	80	0·68
		100	16	12	170	0·66
		100	16	7·8	140	0·75
		200	15	6·8	160	0·68
		200	13	8·3	270	0·76
		200	12	6·0	150	0·70
		200	11	4·1	110	0·72
		200	11	4·6	110	0·69
		200	12	6·2	180	0·74
		200	12	9·4	180	0·64
		200	12	4·8	150	0·75
		200	12	5·2	200	0·80
		200	12	5·4	120	0·66
		200	12	5·6	160	0·73
		200	13	7·9	200	0·70
		200	12	5·6	120	0·66
		200	12	4·4	120	0·72
		200	15	16	330	0·66
		200	15	6·2	120	0·64
		200	20	9·8	270	0·72
		200	15	8·3	210	0·70
		200	15	6·6	120	0·62
		200	16	10	170	0·61
		500	13	7·5	400	0·72
		500	11	4·6	190	0·67

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
7. *Thickness of annual layers of mud, varves—continued*						
Lake Saki, Crimea, U.S.S.R.—*continued*	B.C. 2090–	500	12	7·6	270	0·65
	A.D. 1889	500	12	5·0	220	0·69
	—*continued*	500	12	6·5	270	0·67
		500	13	11	520	0·70
		500	16	8·2	710	0·81
		500	16	9·0	300	0·63
		1000	12	6·4	720	0·86
		1000	12	6·4	400	0·75
		1000	13	9·0	620	0·77
		1000	16	8·6	780	0·72
		2000	12	6·4	820	0·78
		2000	14	8·6	2000	0·87
				114 cases; mean		0·69
Moen, Sogn district, Norway	100–51	50	18	7·8	90	0·76
	50–1	50	15	9·4	130	0·81
	0–51	50	27	14	160	0·76
	52–101	50	23	14	170	0·78
	102–151	50	16	6·4	80	0·79
	152–201	50	16	10	90	0·68
	202–251	50	16	12	95	0·63
	252–301	50	18	17	210	0·78
	302–351	50	24	28	200	0·61
	352–401	50	15	8·4	75	0·68
	402–451	50	19	20	200	0·72
	452–501	50	19	16	140	0·66
	502–551	50	13	6·5	42	0·58
	552–601	50	8·8	5·0	52	0·72
	602–651	50	12	4·8	62	0·79
	652–701	50	17	16	180	0·75
	702–752	50	19	10	110	0·74
	753–802	50	17	6·6	65	0·71
	803–852	50	13	11	150	0·80
	853–902	50	17	15	180	0·78
	100–1	100	16	8·7	150	0·73
	0–101	100	25	14	280	0·76
	102–201	100	16	8·5	140	0·72
	202–301	100	17	15	230	0·70
	302–401	100	19	21	300	0·68
	402–501	100	19	18	240	0·66
	502–601	100	11	6·2	160	0·82
	602–701	100	14	12	230	0·76
	702–802	100	18	8·8	140	0·71
	803–902	100	15	13	340	0·82
	100–101	200	21	13	600	0·84
	102–301	200	16	12	260	0·66
	302–501	200	19	20	310	0·60
	502–701	200	13	9·7	320	0·76
	702–902	200	16	11	400	0·78
	100–401	500	19	15	790	0·72
	402–902	500	16	13	800	0·75
	100–902	1000	17	14	1210	0·72
				38 cases; mean		0·73

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
. Thickness of annual layers of mud, varves—continued						
miskaming, Canada . . .	0–49	50	22	4·8	50	0·73
	50–99	50	24	3·3	25	0·63
	100–149	50	23	4·2	55	0·80
	150–199	50	25	3·1	21	0·60
	200–249	50	20	3·6	35	0·72
	250–299	50	20	3·8	44	0·76
	300–349	50	18	3·0	28	0·70
	350–399	50	18	4·4	45	0·72
	400–449	50	15	2·4	28	0·76
	450–499	50	19	3·1	32	0·72
	500–549	50	19	2·7	41	0·84
	550–599	50	18	5·0	74	0·84
	600–649	50	19	2·3	30	0·80
	650–699	50	18	3·1	31	0·72
	700–749	50	14	3·0	15	0·50
	750–799	50	13	3·2	38	0·77
	800–849	50	13	2·7	32	0·77
	850–899	50	11	2·4	21	0·67
	900–949	50	12	7·0	140	0·95
	950–999	50	24	5·9	70	0·77
	1000–1049	50	22	3·8	22	0·54
	1050–1099	50	21	3·3	33	0·72
	1100–1149	50	19	3·9	51	0·80
	1150–1199	50	10	3·3	52	0·86
	0–99	100	23	4·5	97	0·79
	100–199	100	24	3·8	85	0·80
	200–299	100	20	3·7	52	0·68
	300–399	100	18	3·8	51	0·66
	400–499	100	17	3·4	100	0·87
	500–599	100	19	4·0	100	0·83
	600–699	100	18	2·8	50	0·74
	700–799	100	14	3·2	62	0·76
	800–899	100	12	2·8	79	0·85
	900–999	100	18	8·8	360	0·95
	1000–1099	100	22	3·6	50	0·68
	1100–1199	100	15	5·4	200	0·92
	0–199	200	23	4·1	120	0·73
	200–399	200	19	3·8	93	0·69
	400–599	200	18	3·8	200	0·86
	600–799	200	16	3·7	220	0·89
	800–999	200	15	7·2	560	0·94
	1000–1199	200	18	5·8	420	0·93
	0–299	300	22	4·3	320	0·86
	300–599	300	18	3·8	200	0·79
	600–899	300	15	3·9	350	0·89
	900–1199	300	18	6·9	780	0·94
	0–399	400	21	4·6	500	0·89
	400–799	400	17	3·9	420	0·88
	800–1199	400	17	6·7	1070	0·96
	0–599	600	20	4·6	700	0·88
	600–1199	600	16	5·9	1130	0·92
	0–1199	1200	18	5·6	1530	0·88

52 cases; mean 0·79

TABLE 14—*continued*

Station and phenomenon	Period	N	M	σ	R	K
8. *Miscellaneous*						
Sunspot numbers	1751–1788	38	56	39	300	0·7[illegible]
	1789–1826	38	28	26	260	0·7[illegible]
	1827–1864	38	57	34	230	0·6[illegible]
	1865–1902	38	40	34	280	0·7[illegible]
	1903–1940	38	45	31	260	0·7[illegible]
	1751–1826	76	42	36	820	0·8[illegible]
	1789–1864	76	42	34	730	0·8[illegible]
	1827–1902	76	49	35	510	0·7[illegible]
	1865–1940	76	43	32	450	0·7[illegible]
	1751–1864	114	47	36	910	0·8[illegible]
	1789–1902	114	42	34	800	0·7[illegible]
	1827–1940	114	48	34	750	0·7[illegible]
	1751–1902	152	45	36	840	0·7[illegible]
	1789–1940	152	43	33	760	0·7[illegible]
	1751–1940	190	45	35	840	0·7[illegible]
					15 cases; mean	0·7[illegible]
Wheat prices	1500–1589	90	98	22	210	0·6[illegible]
	1590–1679	90	100	19	240	0·6[illegible]
	1680–1769	90	99	21	270	0·6[illegible]
	1770–1869	100	100	20	290	0·6[illegible]
	1500–1679	180	99	20	290	0·5[illegible]
	1590–1769	180	100	20	290	0·6[illegible]
	1680–1869	190	99	20	370	0·6[illegible]
	1500–1769	270	99	21	280	0·5[illegible]
	1590–1869	280	100	20	310	0·5[illegible]
	1500–1869	370	99	20	380	0·5[illegible]
					10 cases; mean	0·61[illegible]

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ORDINARY MEETING

17 April, 1956

WILLIAM KELLY WALLACE, C.B.E., President in the Chair

The Council reported that they had recently transferred to the class of

Members

...nham, Kenneth Guenott.
...ind, Hugh George, T.D.
...llins, Cyril Austen.
...odsir, James Archibald, M.C.
...ay, George, B.Sc. (*Glasgow*).
...nes, John Mansel.
McLean, Ronald Alfred Milner, B.Sc. (*Queen's*).
Morton, Stanley Osborne, B.Sc. (*Belfast*).
Muir, Robert Ballantine, B.Sc. (*Glasgow*) (*Lt-Col.*).
Smyth, Walter Vernon, B.Sc. (*Belfast*).

...d had admitted as

Graduates

...bbey, William Byland, B.A. (*Cantab.*).
...well, Brian Frank.
...allantyne, Desmond Trevor.
...ell, David Rennie, B.Sc. (Eng.) (*Rand*), Stud.I.C.E.
...enton, Graham Lloyd, B.Sc. (*Birmingham*), Stud.I.C.E.
...nham, Alan John, B.Sc. (Eng.) (*London*), Stud.I.C.E.
...oss, Michael Henry.
...oyce, James, B.Sc. (*Belfast*).
...ramwell, Frederic John, B.Sc. (Eng.) (*London*), Stud.I.C.E.
...urnell, Anthony John, B.Sc. (*Manchester*), Stud.I.C.E.
...urt, David John, B.Sc.(Eng.)(*London*), Stud.I.C.E.
...harles-Jones, Wilmot Selwyn, B.A. (*Cantab.*), Stud.I.C.E.
...how Che King, B.Sc. (*Hong Kong*).
...lark, John Finlay, Stud.I.C.E.
...lements, Christopher Hugh, B.Sc. (*Leeds*), Stud.I.C.E.
...ollinson, Peter Abbey Johnson, B.Sc. Tech. (*Manchester*), Stud.I.C.E.
...oombs, Bram Stewart.
...ostelloe, Michael Joseph, B.E. (*National*), Stud.I.C.E.
...ellar, Geoffrey Bertnal.
...raper, James Lewis, B.Sc. (Eng.) (*Natal*).
...unlop, John Newlands, B.Sc. (*Glasgow*), Stud.I.C.E.
...ox, Dennis, B.Sc. (Eng.) (*London*), Stud.I.C.E.
...ranklin, Roger, B.A. (*Cantab.*).
Friedler, Sali, B.Sc. (*Glasgow*).
Gailor, Harold John, B.Sc. (Eng.) (*London*).
Hammett, Paul Alan, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Harris, Kenneth Arthur, Stud.I.C.E.
Horseman, Peter Kenneth, Stud.I.C.E.
Hughes, John George.
Jackson, Robert Hay, B.Sc. (*Aberdeen*), Stud.I.C.E.
Jermy, Barrie Stuart, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Kuruppu, Upali Sirmath, B.Sc. (*Ceylon*), Stud.I.C.E.
Lamont, James Sloan, B.Sc. (*Belfast*), Stud.I.C.E.
McGookin, John Scott, B.A. (*Oxon*).
McMillan, Colin Gordon, Stud.I.C.E.
McNulty, Eneas Patrick, B.E. (*National*).
Marsden, John Reginald, B.Sc. (Eng.) (*London*).
Maxwell, John Neil, B.Eng. (*Liverpool*).
Munro, Ian Whitelaw, Stud.I.C.E.
Munro, John, B.Sc. (*Glasgow*).
Nanda, Vidya Sagar Roora Mal, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Noble, Richard Allen.
Norman, Arthur, B.Sc. (*Birmingham*), Stud.I.C.E.
Norris, Reginald Dennis Henry, Stud. I.C.E.
Nutter, John Raymond, B.Eng. (*Sheffield*), Stud.I.C.E.
Ogden, James Padgett, B.Sc. (Eng.) (*London*), Stud.I.C.E.

Olawoye, Ebun, B.A., B.A.I. (*Dublin*).
O'Neill, Timothy Christopher, B.E. (*National*).
Osborne, David John, B.Sc. (Eng.) (*London*), Stud.I.C.E.
Page, Edwin George, B.Sc. (Eng.) (*London*).
Park, James, B.Sc. (*Edinburgh*), Stud. I.C.E.
Partridge, John Roger, B.A. (*Cantab.*).
Perkins, James Allen, B.Sc.Tech. (*Manchester*).
Pet, John Mollett, B.Sc. (Eng.) (*Natal*), Stud.I.C.E.
Phillips, David Vernon.
Pickering, Hugh Antony, B.Sc. (*Bristol*).
Plant, Alexander Valentine, B.Sc. (*Glasgow*).
Rattley, Gerald Ivor, B.Sc. (Eng.) (*London*).
Snaggs, Kenneth Bertram, B.Sc. (*Wales*), Stud.I.C.E.
Thompson, John Bernard, B.Sc. (*St Andrews*).
Tonge, Geoffrey Harold, B.Sc. (*Leeds*), Stud.I.C.E.
Tsoi Shiu Foo, B.Sc. (*Hong Kong*).
Uglow, Richard John, B.Sc. (*Bristol*).
Wilden, Derek Laurence.
Wilson, John Trevor.
Wong, Franklin Kai Cheong, B.Sc. (*Hong Kong*), Stud.I.C.E.
Yarwood, David James Dewar, B.A. (*Cantab.*).

and had admitted as

Students

Akeroyd, Frank Maurice Leonard.
Alderson, Geoffrey Stanley.
Ansari, Syavash Amir.
Aquilina, Charles Vincent.
Balasubramaniam, Elaguppillai.
Beckett, John Nigel.
Blaxland, Michael Thomas.
Bourn, Brian Frederick.
Brown, Brian Aubrey.
Bull, Malcolm.
Bushell, Richard Trenchard.
Carter, Raymond Maurice Edward.
Chorley, Robert Michael.
Christopherson, James.
Cobb, William Albert.
Colley, Derek.
Compston, David Gerald.
Crabtree, Edward.
Crainey, Robert Brannan.
Davidson, Barrie Graham.
Davidson, Daniel.
de Mel, Widanelage Roy Premadasa.
Dufour, Peter Andrew Hyatt.
Eggleston, Brian Charles.
El-Amin, Akram Ismail Mohamed.
Fairhurst, John Arthur.
Fawcett, Frank Birkinshaw.
Gardiner, Michael John.
Gibbs, John Robert.
Haddon, Raymond Arthur William.
Hatt, Michael John.
Healy, Peter James.
Hedges, William Sydney Garth.
Heslam, David Somers.
Kemble, John Reginald.
Koniotes, Michael John.
Lock Seng Wong.
Lotlikar, Yeshwant Dattaram, B.E (*Bombay*).
McDonald, John Bede.
McGonigle, John Patrick.
Mahendran, Robin.
Majhi, Anil Krishna.
Meek, Geoffrey Edgar.
Meeke, Ian Barrie.
Morgan, Eric David.
Musgrave, Brian Wilfred.
Ng Chuan Lim.
O'Brien, Noel William.
Oldfield, John Edward.
Patchett, Robert Glyn.
Pemberton, Richard Cooper.
Poole, Alan Charles.
Pretsell, James.
Quan Bing Kuen.
Qureshi, Asghar Ali.
Remmington, Philip Oliver.
Riley, John.
Rodgers, Michael James Arthur.
Rooney, Peter.
Rossington, Antony Bevan.
Rowlands, Brian William.
Rowlands, John Barrie.
Sands, Martin John.
Sharples, Leon Roland.
Sinnott, Adam Ramsay.
Smith, Brian Charles.
Smith, Colin Mitchell.
Snelson, Christopher Wainwright.
Stevenson, Thomas Davidson.
Stockel, Colin Thomas.
Sumner, Leonard.
Tomson, Harold Richard.
Waller, Edwin James.
Walton, Raymond.
Watson, William John.
Watts, John Walter.
Whitehead, Richard David.
Wight, Kenneth Royston.
Wild, Ian.
Williams, Trevelyn.

The following Paper was submitted for discussion and, on the motion of the esident, the thanks of the Institution were accorded to the Author.

Paper No. 6152

THE GLEN SHIRA HYDRO-ELECTRIC PROJECT

by

*** John Paton, M.I.C.E.**

SYNOPSIS

The Paper describes the development, layout, and design of the Glen Shira Project of North of Scotland Hydro-Electric Board. These works, which are at an advanced ge of construction and partially commissioned, are designed to produce 80 million units nually at 20% load factor.

The topography and geology of the site are reviewed since these factors had a major luence on the design and layout. Features of particular interest are dealt with in some ail. They include the main dam (2,250 ft long by 133 ft high) of round-head buttress m, the lower dam, which incorporates an earth embankment with a thin reinforced ncrete core, the pump-storage installation of the upper generating station, the steeply-lined pressure shaft and the lower generating station, which is underground, and the akes for the stream diversions, which have been specially designed to deal with the avy load of debris carried downstream in times of flood.

Although the Paper is devoted principally to the design and development of the works, nstructional matters of special interest are included in the text.

INTRODUCTION

HE Glen Shira Project of the North of Scotland Hydro-Electric Board was referred briefly by Fulton,[1] and certain sections were described in the discussion on a recent per by Jaeger [2] dealing with pressure shafts and underground power stations. he scheme incorporates a number of features which were introduced to meet the rticular circumstances and conditions and it is thought these may be of special terest. These features are therefore dealt with in some detail in this Paper, hereas the general descriptive outline of the scheme and the sections, which are milar in form to other hydro-electric works previously described, are only dealt th briefly to provide the general background.

The project has been designed to harness the headwaters of the Rivers Shira, yne, and adjacent watercourses situated between Loch Fyne and Loch Awe in gyllshire, Scotland, for the production of hydro-electric energy which is fed into e grid to meet peak-load demands. The works are conveniently situated to the dustrial power-consuming areas in mid-Scotland and, on completion, will produce lly 80 million units per annum.

As with any project of this kind, and certainly to a very marked degree in this articular case, the form and layout of the works have been influenced largely by e topographical features of the area. In following the arrangement of the scheme

* The Author is a Partner in the firm of Babtie, Shaw & Morton, Consulting Engineers.

[1] The references are given on p. 618.

it is necessary to have an understanding of the main geographical features, particularly the course of the River Shira in its descent towards Loch Fyne and the arrangement and relative levels of the tributary streams and adjacent watercourses. The general layout is shown in Fig. 1, Plate 1, and the hydraulic section is reproduced in diagrammatic form in Fig. 2, Plate 1.

The catchment area is mainly above the 1,000 contour (Ordnance Datum) and rises at the summit of Ben Bhuidhe to 3,106 ft above sea level. Following completion of the preliminary surveys in 1946, six rain gauges were installed in the area and continuous records have been kept since then. Relating these records to the long-term particulars for other gauging stations, the average annual rainfall for the catchment is estimated to be 105 in.

The annual rainfall recorded at the site of the principal works during the years 1949 to 1954 was 117, 103, 95, 79, 111, and 118 in., giving a monthly average of 8·7 in. During that period the maximum weekly rainfall recorded was 8·8 in. and the maximum daily rainfall 3·6 in. These details will serve to indicate that, although the area is admirably suited for hydro-electric development, construction progress on these upland sites can be seriously hampered by rainfall, quite apart from the effects of frost, snow, and severe gales, which can also dislocate the continuity of constructional activity particularly during the winter months.

Geologically, the area occupied by the works is part of what is termed the Dalradian Metamorphic Complex—an assemblage of altered sedimentary and igneous rocks which makes up a large part of the Grampian Highlands. The main subdivisions of this complex represented in the works area are phyllites, schists, and epidiorite masses with numerous thin intrusions of igneous rocks and, at the northern extremity of the site, large zones of limestone. The phyllites, which are formed by the metamorphism of calcareous shales, are for the most part very soft and fissile, resulting in poor foundations and requiring support in tunnels and underground chambers. Schists occupy the south-easterly portion of the site and comprise schistose grits, quartz-schists, and mica-schists which are generally sound and fairly massive, providing better foundations.

In the upper reaches of the River Shira the valley is relatively flat and there is a good natural storage basin situated at an elevation above the 1,000-ft contour. This is the only suitable site within the region for the provision of a large reservoir. The direct catchment area upstream of the site of the dam is approximately 4½ sq. miles, but it is economically practicable to extend this catchment by diversion of the headwaters of the River Fyne and other adjacent watercourses which at present flow either to Loch Fyne or Loch Awe.

Preliminary reconnaissance indicated that there are no attractive sites for dams along the valley of the River Shira downstream of the site referred to, so that multi-stage development along the course of the river was not suited to the conditions. It thus appeared that the basic essentials of the scheme should take the form of a high-level main storage reservoir serving an aqueduct following the shortest economic route to a power station situated at or near sea level. From the preliminary surveys it was clear that extensive high-level catchments could be brought into the scheme by diversion of the three main tributaries of the River Shira, which lie along the most favourable route for the main tunnel. A detailed study of site conditions showed that the total catchment area could be augmented most effectively by the adoption of a two-stage layout, with the high-level catchments diverted into the main storage basin where practicable and the lower upland catchments, particularly those lying along the line of the main tunnel, diverted into a lower reservoir formed

within a suitable range of elevation below the main reservoir. Further detailed investigation indicated that, although the site conditions for provision of a lower storage reservoir were not very suitable, development on these lines would be the most economic overall arrangement.

The project as finally developed comprises a main reservoir having a top water level of 1,108 O.D. and an effective storage capacity of 750 million cu. ft (equivalent to 15 million units of electricity in reserve) formed within the direct catchment of [illegible]½ sq. miles, into which the upper diverted catchments totalling 8¾ sq. miles are fed by means of diversion tunnels and aqueducts. Water drawn from the main reservoir will be fed into the lower reservoir through the upper generating station known as the Sron Mor station. The tail-race water discharging from this station into the lower reservoir will be augmented by the run-off from the small catchment area and the diverted catchments of the Beinn Ghlas, Brannie, Kilblaan, and Clachan Burn areas, which total 8 sq. miles. Of these diverted catchments the last three are fed into the main pressure-tunnel system, the intake levels being so arranged that, when the main generating station is not operating, the run-off from the Brannie, Kilblaan, and Clachan areas flows in reverse through the main tunnel for storage in the lower reservoir. Water is drawn from the lower reservoir to supply the main generating plant at Clachan near the head of Loch Fyne and the tail-race water is discharged into the River Fyne.

The effective storage capacity of the lower reservoir, which has a top water level of 970 O.D., is only 55 million cu. ft (equivalent to 1 million electrical units), which is very small in relation to the catchment area serving this stage. Although the scheme is not yet in full operation, it is anticipated that spillage from the lower reservoir can be eliminated by a combination of the following means:

(1) By reserving the storage in the upper reservoir mainly for balancing seasonal variations.

(2) By careful control of the output of the upper station in relation to the actual run-off from the lower catchment areas.

(3) By occasionally operating the upper station in reverse to pump a proportion of the inflow to the lower reservoir up to the main storage reservoir.

Provision is made in the scheme to pass compensation water for fish down the River Shira and water will not be abstracted from the River Fyne until the flow at the intake there exceeds 3 m.g.d. The terms agreed require that the minimum flow in the lower reaches of the River Shira shall be maintained at 5 m.g.d. with "freshets" of 45 m.g.d. on 16 days between June and September.

Main dam

To provide the requisite storage a dam approximately 2,250 ft long having a maximum height of 133 ft above the level of the river-bed (148 ft above foundation level) is being built in the upper reaches of Glen Shira. The general layout and principal details of the structure are illustrated in Figs 3, 4, and 5, Plate 1, and the leading particulars are summarized in Table 1. Figs 6, 7, and 8 (pp. 602–3) show stages in the construction of the dam.

The geological conditions at the site of the dam were explored by means of trial borings and these confirmed that the rock structure was complex, comprising mainly soft phyllite with occasional hard bands of quartzite and quartz-schist and an extensive zone of limestone. Having regard to the variable nature of the rock strata

TABLE 1.—DAMS

Structure and type	Max. height: ft	Length: ft	Volume of concrete: cu. yd	Volume of earth fill: cu. yd	Volume of excavation: cu. yd
Main dam Round-head buttress type	133	2,250	260,000	—	135,000
Lower dam Concrete gravity section	58	400	18,000	—	15,000
Earth-fill (non-overflow) section . .	53	600	—	80,000	—

it was considered essential to provide a structure which would distribute the foundation pressures with reasonable uniformity within the wide range of loading conditions. Preliminary designs for dams of the buttress type were examined in detail and economic comparison made with designs for mass gravity, slotted gravity, and rock-fill dams. The conclusions reached from these investigations can be summarized briefly as follows:

> For the end portions, extending to a height of about 55 ft, mass gravity construction was found to be the most economical form.
>
> Applying the same design criteria with respect to stresses in the foundation rock under the dam, for the main portion of the structure (exceeding a height of approximately 55 ft), the relative cost of rock-fill, mass gravity, and round-head buttress was found to be of the order 1·4 : 1·25 : 1. The form of concrete structure giving the most favourable distribution of pressure on the foundation rock was the round-head buttress type. An alternative design was prepared for a slotted gravity form of dam with the upstream face practically vertical and having open cavities on the downstream side for relief of uplift. The cost of this type was found to be slightly greater than the round-head buttress and the distribution of pressure on the foundation rock was much less favourable for the conditions pertaining at this site. Further investigations were undertaken to determine the relative merits of the round-head buttress form and the diamond-head form. These investigations indicated that, even if the rates for curved shuttering for the upstream face of the round-heads proved to be appreciably greater than those for straight work, the round-head buttress form would be more economical. It was thought that the curved shuttering need not be highly priced since there was scope for a substantial number of re-uses of the shutter panels and this was proved to be so when the tender prices were received.

The form of construction thus selected as being most suited to the conditions comprises thirty-seven round-head buttresses spaced at 50-ft centres. To allow for the effects of concrete shrinkage and to accommodate variations in the deformation of the foundation strata under load, the individual buttresses are not poured in contact with one another but are spaced 5 ft apart to receive wedge-shaped closing sections which are poured after the shrinkage is substantially complete, with the main buttresses raised to a considerable height. The butting faces are coated with a bituminous emulsion to permit freedom of movement and the joints are sealed

near the upstream face with a crimped copper water-bar behind which a diamond-shaped recess has been formed to receive a bituminous sealing compound.

Analysis of horizontal sections through the concrete and in the plane of the foundations was carried out and the stability factor and stresses were computed.[3] Limiting criteria were set for the design as follows:

(1) Sliding factor—not greater than 0·7.
(2) Factor of safety against overturning—not less than 1·7.
(3) Maximum principal compressive stress in the foundation rock immediately under the dam—not greater than 10 tons/sq. ft.
(4) No tensile stresses in the concrete adopting the usual assumption that plane sections, both in the concrete and in the contact surface with the foundation rock, remain plane under load.

The design analysis included the usual conditions of loading, namely:

(*a*) Reservoir empty.
(*b*) Reservoir full at maximum flood level.
(*c*) Reservoir full at maximum flood level with uplift acting on the concrete and foundation rock.

Condition (*c*) is the most severe, the magnitude of the uplift having a considerable influence on the design. The uplift assumptions on which the designs were prepared are shown in Fig. 9. These assumptions with respect to the distribution of uplift pressures were selected to allow for the combined effect of the drains (see Fig. 4, Plate 1), which are open to inspection, and the natural drainage into the spaces between the buttresses.

The maximum principal stresses calculated in a plane through the centre-line of the buttresses are summarized in Table 2.

TABLE 2.—MAIN DAM—STRESSES

Element of structure	Stress: lb/sq. in.	
	Reservoir full	Reservoir empty
Maximum stress (compressive) in buttress head (in plane of buttress)	60	110
Maximum stress (compressive) in stem of buttress	240	75
Maximum principal stress at foundation level	150	105

Loading tests were carried out at the site to determine the probable deformation of the foundation rock strata under loading conditions. The equipment used enabled the deformation to be measured on loading small areas 2-ft square by increments up to a limit of 25 tons/sq. ft and these tests served to indicate that the deformation to be expected under the working conditions would be of a minor order, probably in the range 0·2 to 0·3 in. under the highest buttresses.

Inspection shafts, generally of 4 ft 6 in. dia., are provided within the mass of the buttress round-heads as shown in Figs 4 and 5, Plate 1. Apart from their main function for inspection of the drainage arrangements, these serve during the construction of the dam in providing an additional cooling surface, thereby reducing

the temperature gradient through the mass. Care was taken in detailing these and any other openings within the dam to avoid sharp corners and changes of shape which could result in concentration of stress. The designer had access to the full report[4] on a series of photoelastic experiments on the stress distribution in a diamond-head buttress dam of similar proportions, which confirmed that the openings proposed were suitable as to dimension and form and that the calculated stresses were generally of the order indicated by photoelastic analysis.

Pressure grouting, carried out in stages, is in hand to form a grout curtain under the cut-off. Up to the present, drilling has been undertaken to a maximum depth of 130 ft below scarcement level and the quantity of cement injected (dry weight) is equivalent to an average intensity of 0·67 lb/sq. ft calculated over the grouted area below the bottom of the cut-off. The sections treated to date include the limestone region, which has not required appreciably more than the average quantity per unit area of grout curtain.

The concrete for the hearting of the dam contains 380 lb. of cement per cubic yard and the maximum aggregate size is 2½ in. The exposed surfaces are faced with a richer mix containing 615 lb. of cement per cubic yard with a maximum aggregate size of 1½ in. As in the other main sections of the construction works the concrete is weighbatched and a high proportion of the sand used is obtained from the site quarry plant, the ratio of rock sand to imported natural sand being generally 75 : 25. The batching plant, which has a rated output of 100 cu. yd/hour, is of modern design and includes two 2-cu. yd mixers from which the concrete is fed by transfer track to overhead travelling cableways. It was realized at an early stage that, on account of the overall dimensions of the structure, which contains about 260,000 cu. yd of concrete, the plant necessary for its construction required special consideration and, following comparison with a number of possible schemes, two 10-ton radial travelling cableways were ordered. These machines, which were offered on hire to the civil engineering contractors who tendered for the works, are arranged on a span of 2,100 ft to cover the main sections of the dam. Portable mobile cranes moved from block to block by the cableways are used for lifting the shuttering panels, thus reserving the cableways mainly for placing concrete which is handled in 4-cu. yd skips. Outputs of 3,000 to 3,500 cu. yd are quite usual for a twelve-shift week and a peak figure of 4,000 cu. yd has been achieved. The corresponding rate of progress in the raising of the dam compares quite favourably with that which is generally attained in building a gravity dam of similar height in which the shuttering is much simpler and the volume of concrete substantially greater.

The concrete has been brought up in 5-ft lifts and, since the individual buttresses are spaced about 5 ft apart, the contractor is free to proceed concurrently with adjacent blocks as may be desired. Immersion vibrators are used in placing the concrete and the length of pours in the stems of the buttresses is limited to a maximum of 50 ft as a precaution against shrinkage cracking. Precast construction has been used on a limited scale for sections which lend themselves to this technique.

Details of the draw-off section of the dam are shown in Fig. 5, Plate 1. A worthwhile economy has been effected by arranging the inlet to the penstock vertically above the scour inlet, resulting in a compact assembly with one emergency gate designed to serve either of the openings as required.

Sron Mor generating station

The Sron Mor station is situated alongside the River Shira near the point where the river channel enters the lower reservoir. The power-station building, which is

steel framed and clad in random masonry, is arranged as shown in Fig. 10, Plate 2.

Preliminary analysis, which had perforce to be based on hypothetical cases for the Shira plant operating as part of a connected network in relation to the seasonal distribution of rainfall, indicated that there was a good case for a reversible pump-storage installation. The lower reservoir, which is fed by 38% of the total catchment area, has a capacity rather less than 7% of the total storage of the scheme but water raised 100 to 130 ft from the lower reservoir to the upper, where there is ample storage, can be held in reserve for hydro-power generation during peak periods over the effective head of both stations, which totals almost 1,100 ft. The addition of the pump-storage equipment should make for greater flexibility in the operation of the generating plant enabling the top water level in the lower reservoir to be held close to spillway level, thus maintaining the maximum head on the main generating plant at Clachan, with obvious advantages.

Water will be fed to the Sron Mor station from the main reservoir, about 240 linear yd upstream, through a 9-ft-dia. steel penstock laid in trench and protected with a surround of concrete. The generating plant, which will be remote controlled from the Clachan control room, comprises a Francis turbine coupled to an induction generator of 5,000 kW capacity designed for operation under a gross head of 138 ft, which is created by the construction of the upper dam. The motor/generator is mounted horizontally between the turbine and a centrifugal pump, and provision is made for uncoupling the latter so that the windage and friction losses of the pump impeller and bearings (which are of the order of 1%) do not reduce the efficiency of the turbo-alternator unit. For full-load output the turbine requires 520 cusecs and the efficiency of the turbo-generator unit is given as 85%. When pumping and delivering 364 cusecs against the design (total) head of 143 ft the overall efficiency of pump and motor is 83%, corresponding to an input to the motor/generator of [illegible],100 kW. Special equipment is provided to facilitate the dewatering of the turbine when the pump is going into service and to reduce the time required for uncoupling the pump from the turbo-generator assembly.

The pumping will be done at week-ends or whenever there is spill water. Since the pumping head will only be a tenth of the full head through which the pumped water will be utilized for power, the economic advantages are particularly favourable. The effect will be that power, which would otherwise be disposed of as "spill" energy, will be produced at times of peak load for use in replacement of units which would otherwise have to come from high-cost thermal stations and would thus represent a value of about twice what the energy would have been worth if it had been simply "spill."

The installation is the first of its kind in the United Kingdom and it is hoped to obtain useful data for further application regarding the value of pump-storage plant on a hydro-electric network serving local and peak-load requirements. This is of particular importance at the present time when consideration is being given to the advantages of hydro-electric pump-storage installations working in conjunction with nuclear base-load generating plants.

Lower reservoir works

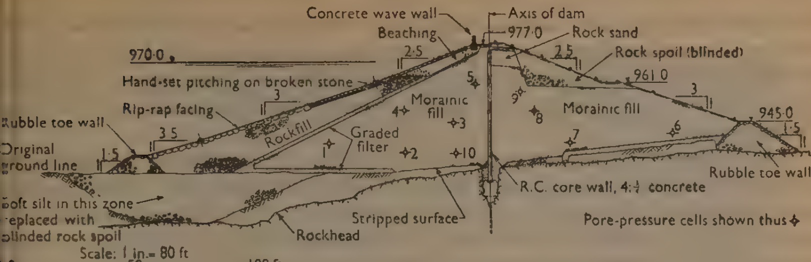
Although the desirability of two-stage development, involving the provision of a lower storage basin, was well established on engineering and economic grounds site conditions were by no means favourable to the formation of a reservoir within the desired range of elevation. The only feasible site involved the construction of a dam

in two separate sections, one of these being located immediately upstream of a waterfall about 40 ft high and separated from the other section to the west by a massive rock intrusion. In addition, a low cut-off embankment was required to prevent seepage through the watershed at the western extremity of the basin. The site has been developed to the economic limit but the reservoir storage is very small in relation to the demand of the generating plant installed at the Clachan station, thus giving rise to the possibility of a rapid drawdown of the water level. The general arrangement of these structures is shown in Fig. 11, Plate 2, and Fig. 12 and Fig. 13, (p. 618), together with certain details to which further reference is made in the text, and the leading particulars of the dams are given in Table 1.

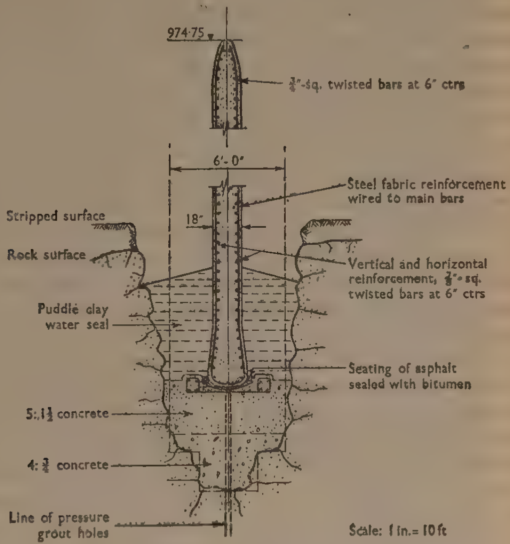
For the section of the dam upstream of the waterfall, which incorporates the spillway, concrete gravity construction was considered the most suitable form. To conform with the setting of the natural rock abutments and with a view to increasing the clearance between the top of the waterfall and the spillway, the dam has been curved in an upstream direction to a radius of 300 ft. The structure so arranged has a length of 400 ft and a maximum height at spillway crest level of 58 ft. The dam was poured in blocks each 34 ft long, leaving 6-ft-wide contraction gaps which were closed after an interval of 8 weeks.

Grouting of the foundations was undertaken to provide an impervious cut-off. The strata, which comprises phyllite with occasional hard bands of igneous rock, did not take any appreciable quantity of grout apart from isolated zones where the igneous intrusions were brecciated by faulting. The grout curtain was formed by injection from inclined holes at rock-head level along the upstream face and spaced generally at 10-ft centres. Drilling extended to a maximum depth below rock head of 120 ft and the total quantity of cement injected was equivalent to an average of 1·2 lb/sq. ft of curtain area.

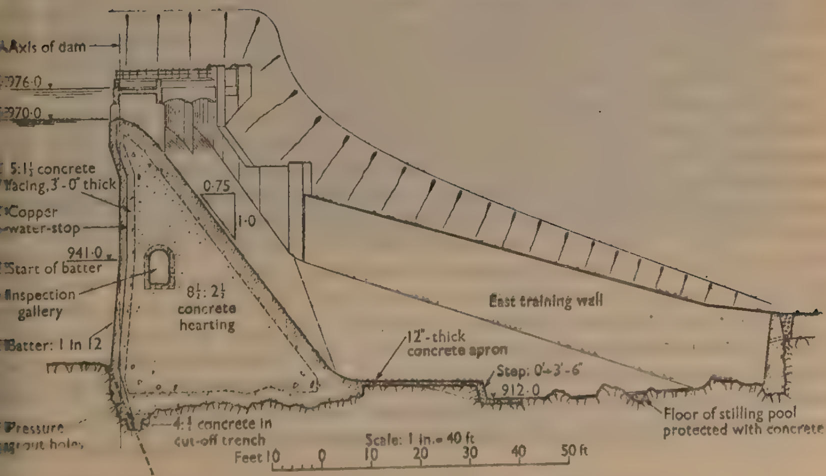
A feature which required special consideration was the arrangement of the spillway bucket and relative works. Having regard to the broken nature of the rock at the toe of the spillway dam, which is within the zone of a minor fault, and to the close proximity of the waterfall, it was obvious that any significant erosion of the bed by discharge of spill water could ultimately endanger the foundations of the structure. The works had therefore to be designed so as to eliminate all possibility of scour erosion. A preliminary layout was prepared to suit the site conditions and this was studied by means of hydraulic model experiments, the final form being altered and improved by reference to the performance on the model. The layout, as finally developed, incorporates two stilling pools as shown in Fig. 11, Plate 2. The upper pool serves to form a standing wave for dissipating the energy of the spill water, but the model tests revealed that the stability of the hydraulic jump was disturbed at high rates of flow by the turbulent conditions within the pool. These conditions arise from the manner in which the flow enters the pool, being in the form of two impinging streams, one from the centre and right-bank portion of the spillway projected in a downstream direction and the other entering at an angle from the left bank owing to the curvature of the spillway and the slope of the natural rock surface near the left bank. (See details in Fig. 11, Plate 2.) Experiments on the model demonstrated that the impinging effect of the streams could be minimized by forming a step in the floor of the pool (marked XY in Fig. 11, Plate 2), such that the stream projected in a downstream direction enters the pool above the level of the other stream. In the full scale the step referred to varies in height from zero to 3 ft 6 in. and was formed quite simply by terminating the concrete apron of the spillway on the curved alignment shown, the harder rock intrusions at the lower end



TYPICAL SECTION OF EARTH EMBANKMENT



DETAIL OF CORE WALL AND CUT-OFF



SECTION OF CONCRETE GRAVITY SPILLWAY DAM AND STILLING BASIN

FIG. 12.—SOME DETAILS OF LOWER RESERVOIR DAMS

of the pool being retained and the softer zones between sealed with concrete. The lower pool serves to distribute the flow evenly on to the river-bed and to form a standing wave when the scour or compensation valves are discharging. The downstream weir also provides a ready means of measuring the discharge of the compensation water.

At the non-overflow section of the dam west of the rock intrusion referred to, the depth of the moraine ranges from 10 to 20 ft and detailed analysis revealed that an earth embankment would be the most suitable form. The embankment is 600 ft long and has a maximum height of 53 ft. The glacial moraine available for its construction consists mostly of weathered mica-schist containing a considerable proportion of silt-sized particles of rock flour. Samples taken from the borrow pits were tested and classified and were found to vary considerably in composition, grading, and natural moisture content from one zone to another. The corresponding variation in the strength of the fill, together with the necessity to provide for an unusually rapid drawdown of water level, introduced complex problems not generally associated with an embankment of such modest dimensions. Having regard to the range of values obtained from the detailed soil analysis and the corresponding difficulty in assessing reliable values for design, coupled with the uncertain behaviour of some classifications of the material on drawdown, it was decided to install equipment for measuring the pore pressure at selected positions in the fill. The information thus obtained enabled the construction of the embankment to proceed with confidence during periods when the weather was none too favourable and the pore pressures on the initial filling and subsequent lowering of the water level were recorded.

Following a general study of the requirements, alternative schemes for the form of the embankment were developed and examined in detail. The design which was favoured, subject to locating an adequate supply of banking materials of suitable type, comprised a wedge-shaped upstream zone of well compacted impervious fill, increasing in thickness towards the base, backed and supported by a section of well compacted granular filling. Detailed site investigation disclosed that the local deposits of impervious material were very limited and variable in character and could not be relied on to fulfil the requirements. The other scheme was therefore adopted, comprising an embankment of morainic material constructed of the more granular types obtainable, having a watertight barrier in the form of a thin reinforced concrete core wall supported on a concrete plinth extending into sound rock to form the cut-off. The form of the embankment is illustrated in Fig. 12, which also shows the location of the pore-pressure cells.

It will be noted on reference to Fig. 12 that the concrete core, which is generally 18 in. thick, is not bonded into the cut-off but is articulated at the base where it is supported on a concrete saddle in such a manner as to permit of rotation or horizontal drift to accommodate variations in the compaction of the filling, without inducing unnecessary bending stresses. The details adopted for sealing the base of the wall against leakage are shown. The wall is heavily reinforced horizontally and vertically on both faces, the total quantity of steel being equivalent to 3·7 cwt/cu. yd of concrete. A series of experiments was carried out to establish the best combination of reinforcement for crack resistance should the wall tend to deflect appreciably owing to inconsistency in the compaction of the fill. Based on the results of these tests, the pattern of the reinforcement finally chosen comprised square-twisted main bars to B.S. 1144 with a layer of square-twisted fabric reinforcement of 4-in.-square mesh wired to the main bars on each face and spaced to give a minimum cover of 1 in

FIG. 6.—GENERAL VIEW OF MAIN DAM (DEC. 1955)

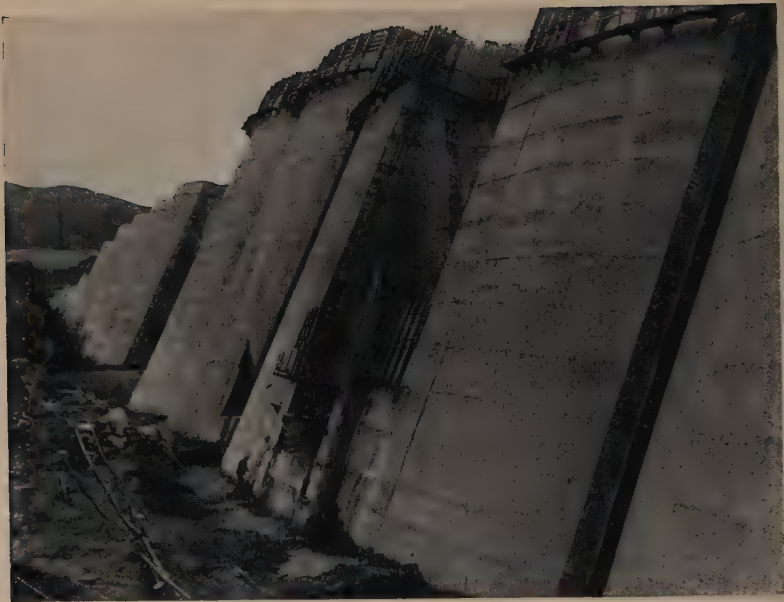


Fig. 7.—Upstream face of main dam (Dec. 1955)

Fig. 8.—Main dam: buttress No. 19 (Dec. 1955)

The wall was poured in lengths of 54 ft with the reinforcement projecting into ntraction gaps 6 ft wide which were concreted (after an interval of at least 4 weeks) short distance ahead as the banking was brought up. Particular attention was ven to the preparation of the construction joints. The outer surfaces of the wall ve been sealed with an application of bituminous emulsion, the finishing coat ing mixed with sand and applied by trowel to form an impervious skin capable of sisting the abrasive effects from the placing of fill alongside.

The filling was put down in 9-in. layers and compacted with 8-ton smooth-wheeled llers, the upstream and downstream zones being brought up together in a uniform anner. The main bulk of the embankment was placed during 1954 and the eather was favourable for this operation during May and the early part of June nen the lower zone was constructed. The natural moisture content in the borrow ts was then about 4% above the optimum value and the filling was placed at rates to 12 ft per month without difficulty. The weather broke about mid-June and e last 6 months of the year were unusually wet. The rainfall for the 4 months ptember to December inclusive averaged 15 in. per month and opportunities for orking with earth-fill were so limited that the progress for some periods fell to less an 2 ft per month, despite the fact that the cross-section per foot of height in that gion was very substantially reduced in volume compared with the lower zones. expedite progress in preparation for commencement of impounding, a proportion rock spoil and crusher sand was introduced near the top of the bank as shown in g. 12.

Markers were set into the core wall so that any movement of its top edge or on a rtical section at the manhole which accommodates the pore-pressure connexions uld be detected. While the embankment was being built and the upper sections the wall panels were not bonded together, a measurable deformation of the top ge was recorded which served to confirm the importance of bringing the filling up enly on both sides with a uniform degree of compaction. Readings to check the gnment of the core wall were taken as the reservoir was filled and have been peated subsequently, but there has been no significant movement since the con-uction of the bank was completed.

The pore-pressure equipment takes the form of a series of hollow plastic cases ving porous stone disks which are buried in the fill as the work proceeds and con-cted to Bourdon pressure gauges by means of small-bore polythene tubing. The stallation, which was designed in consultation with Dr L. F. Cooling of the Depart-ent of Scientific and Industrial Research, has been so arranged that the readings n be continued with the reservoir in service and the gauges have been read at gular intervals. Since the pore pressures recorded during the building of the bankment were generally of a minor order, there was no need to limit the rate of nstruction provided the weather conditions were such as to permit of satisfactory mpaction of the surface layers of fill being placed. Special provisions have been ade for the sudden drawdown condition, the design analysis indicating that this likely to be the most severe to which the embankment will be subjected. For pid conditions of drawdown as assumed, the stability factor of the embankment estimated to be of the order of 1·4 compared with a minimum value of 2·0 for the ner modes of failure investigated.

Impounding was commenced in December 1954 and there have since been con-lerable fluctuations in the reservoir level. Rates of drawdown have been limited a maximum of about 5 ft per day and the changes in pressure recorded at the urdon gauges have followed the variations in reservoir level but damped to a

degree, depending on the distance of the pore-pressure cell from the nearest free-drainage surface. Expressed in another manner, the results show that there is a time lag before the reservoir level is balanced at the pore-pressure measuring point, as might be expected. The data obtained from these observations has been of value in reviewing the validity of the design assumptions with respect to the "drainability" on drawdown of the material forming the embankment.

Main tunnel and pressure-shaft works

The low-pressure section of the main tunnel extends to a length of 21,050 ft and comprises two main sections driven from four portals and a short length commencing at the outlet from the lower reservoir which is joined with the main portion south of the Allt-an-t'Sithein by means of a reinforced concrete aqueduct (see Fig. 2, Plate 1). These works have a finished internal diameter of 10 ft and are concrete lined throughout except for the two stream crossings where steel pipes were introduced.

A circular section was chosen for the tunnel as being the most suitable structural form having regard to the working pressures and the very soft nature of the schist and phyllite in this region. Since the cross-section was not large, only the weakest zones had to be supported with steel arch-ribs and the combined lengths ultimately ribbed extend to about 5½% of the total. Driving conditions varied on account of the variable nature of the rock encountered. Drilling rates through the soft schist were generally good. The quantity of explosive required averaged 5½ lb/cu. yd of rock excavated and short pulls were not infrequent. The overbreak was moderate and on driving averaged about 7% (by volume) on the payment section but this tended to increase when the final trimming was carried out preparatory to lining, the rock exposed having deteriorated by weathering.

A nominal thickness of 8 in. was specified for the concrete lining which was placed by means of a pneumatic "placer" of 1 cu. yd capacity working in conjunction with a telescopic shutter 200 ft long moved forward continuously in 20-ft panels. For the two main lengths of the tunnel the concrete was mixed at a central weigh-batching plant situated at the Brannie Burn crossing and was transported to the placer in remixing cars of 3 cu. yd capacity. Continuous pouring was undertaken from one week-end to the next (twelve shifts) and the results were generally very good. An average rate of about 550 ft per week was attained, including a record weekly advance of 1,020 ft.

The section north of the Allt-an-t'Sithein, which is of reinforced concrete, was carried out by cut-and-cover methods. In this region the hydrostatic pressure is of the order of 25 lb/sq. in. The concrete ring is 9 in. thick and contains 205 tons of reinforcement, equivalent to 2·55 cwt/cu. yd. It was poured in panels 30 ft long with contraction gaps 4 ft 6 in. wide, which were filled during cold weather after an interval of fully 3 months. The longitudinal reinforcement is lapped at the gaps and is continuous over a length of 108 ft between expansion joints. By adopting reinforced concrete construction in this section as an alternative to the use of steel pipes a substantial saving was made and the tonnage of steel required was considerably reduced at a time when the supply position was very difficult.

A feature of the scheme is the inclined pressure shaft and underground power station adopted in preference to an exposed steel penstock on the hillside serving a surface generating station. A comprehensive review of present trends in the design of pressure shafts and underground stations was published in 1955,[2] and it is the

tention of the Author to deal more particularly in this Paper with practical aspects nd problems encountered in the construction of the Clachan works.

The decision to adopt an underground station and inclined pressure shaft was ken following detailed analysis of tender prices received for alternative underound and surface layouts. This investigation indicated that the overall cost for e underground scheme would be of the same order as the surface arrangement. eel was in short supply at that time and a saving of about 350 tons weighed in vour of the underground scheme, which was also preferred on grounds of amenity.

The general arrangement and typical details of the pressure shaft are shown in igs 14 a and b. Since major stream diversions are brought into the tunnel system rough the surge shaft, the location of the upper end of the pressure shaft was etermined largely by site conditions. The arrangement adopted, with the pressure nd surge shafts on the same axis and grade, was developed to facilitate construconal requirements, particularly the handling of the steel lining pipes.

To receive the lining a circular cross-section was chosen, the diameter of the heading r the greater part of the length being 9 ft 6 in. A pilot tunnel was driven from the ortal of the tail-race tunnel following the alignment of the tail-race and passing rough the power-station area. From the upstream wall of the station the full ction was driven on a curved alignment proceeding for approximately 600 ft rising a grade of 1 : 100 and thence on a vertical curve leading to the steep portion pproximately 1,450 ft long, which is inclined at 39° to the horizontal (1¼ horizontal 1 vertical). The steep portion was driven from the bottom without the assistance temporary bulkheads, which are commonly used in Continental practice. The ock spoil was allowed to accumulate on the slope up to about the horizontal axis of e cross-section and was removed at intervals by a scraper loader, located at the ottom of the incline. This machine was put to work as required, such that the oor of the sloping tunnel was generally covered to a considerable depth and there as some measure of control of the spoil in its drift downwards towards the loader. he inclination of the shaft was selected to be just steeper than the natural angle of pose of the rock spoil and proved to be very suitable in relation to the character nd fragmentation of the rock debris. The shaft was driven through quartz-schist ith occasional intrusions of igneous rock in a zone which is much harder than the ica-schist and phyllite encountered in the main tunnel farther north. A favourable rcumstance arose from the fact that the rock strata in this region dips to the northest at an average angle of about 40° so that, in driving the steep portion of the aft, the bedding planes were almost normal to the axis and the tunnel was very cure, no temporary support being required. The tunnel was also remarkably dry. riving rates of 40 ft per week were achieved but progress tended to fall off as the eading advanced up the incline. By excavating small chambers at intervals of pproximately 250 ft for accommodation of equipment, the necessary driving rate as maintained. Some difficulty was experienced in protecting the service pipes om damage and these had to be mounted above the axis of the tunnel to clear the iding mass of rock debris.

Having completed the excavation, the invert was cleaned to sound rock and a ght-gauge track was installed to facilitate erection of the steel lining. The shaft lined with steel pipes from end to end, the size of the heading being just sufficient provide the necessary clearance for installation of the lining. Concrete was olidly packed into the surrounding space and thereafter grouted under pressure. he design of these composite steel-concrete linings is somewhat arbitrary but

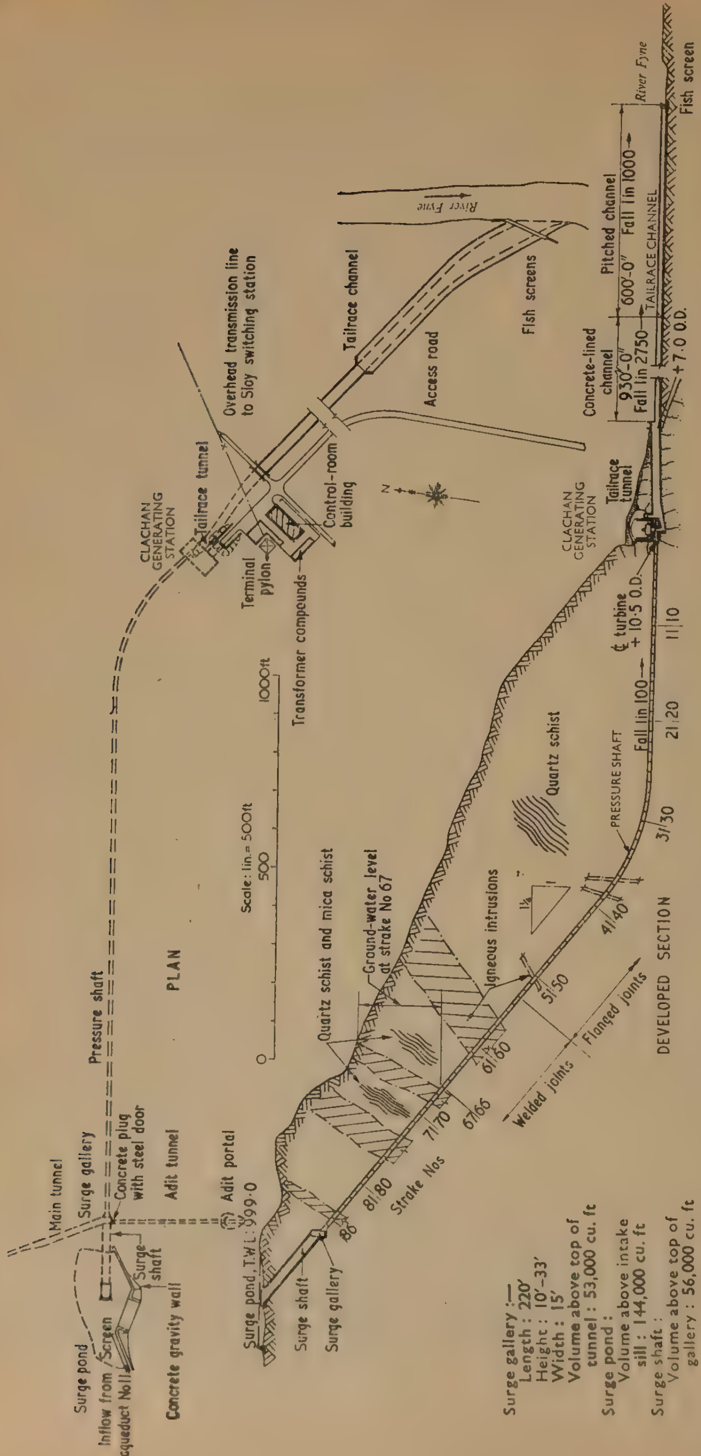
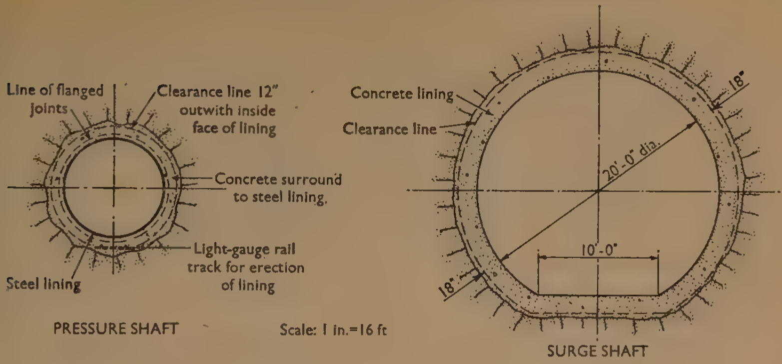


FIG. 14a.—GENERAL ARRANGEMENT OF PRESSURE SHAFT AND SURGE SHAFT



PRESSURE-SHAFT LINING

Strake No.	Internal diameter	Plate thickness: in.	Strake No.	Internal diameter	Plate thickness: in.
1–4	6′ 0″	$1\frac{9}{16}$	29–31	7′ 6″	$\frac{15}{16}$
5–6	6′ 6″	$1\frac{1}{2}$	32–34	,,	$\frac{7}{8}$
7–8	,,	$1\frac{7}{16}$	35–36	,,	$\frac{13}{16}$
9–10	,,	$1\frac{3}{8}$	37–38	,,	$\frac{3}{4}$
11–12	,,	$1\frac{5}{16}$	39–43	,,	$\frac{11}{16}$
13–15	,,	$1\frac{1}{4}$	44–48	,,	$\frac{5}{8}$
16–18	,,	$1\frac{3}{16}$	49–53	,,	$\frac{9}{16}$
19–22	7′ 0″	$1\frac{1}{8}$	54–58	,,	$\frac{1}{2}$
23–25	,,	$1\frac{1}{16}$	59–73	,,	$\frac{7}{16}$
26–28	7′ 6″	1	74–86	8′ 0″	$\frac{7}{16}$

FIG. 14b.—SHAFT CROSS-SECTIONS AND DETAILS OF LINING

nsiderable experience has been gained from the extensive shafts of similar construction on the Continent.

The lining of the Clachan shaft is of mild steel to B.S. 15 (ultimate strength 28 to tons/sq. in.). As a first approximation in developing the design the thickness of ating selected for each section was such that, for the pipe acting independently ith no support from the concrete backing or surrounding rock, the stress on the eel would not exceed the yield point. The thickness determined by this arbitrary ocedure was then investigated by the method outlined by Jaeger,[2] the effect of ck fissures of varying depth being considered. This analysis indicated that the bitrary procedure used in obtaining the first approximation was rather conservative some sections and adjustment was made to give a more balanced design, the ickness ranging from $\frac{7}{16}$ in. at the top to $1\frac{9}{16}$ in. at the generating station where e pipe shell is thickened progressively as the rock cover reduces, the last few ngths being designed for the full hydrostatic head plus the usual allowances for aterhammer effects and corrosion. Details of the steel lining are given in Fig. 14b; will be noted that the finished internal diameter of the shaft is generally 7 ft 6 in. ut is increased to 8 ft towards the top and reduced to 6 ft at the power station.

Consideration was also given to the possible effect of external pressure in the lining when the shaft is empty due to water in the fissures of the surrounding rock. Experience gained on recent high-head Continental schemes has indicated that this is a very important consideration governing the design.[5] The analysis is empirical since the assessment of hydrostatic pressure in the fissures of the surrounding rock mass involves a degree of conjecture. Investigation by the method of analysis proposed by Amstutz indicates that a modest increase in the thickness of the lining increases the resistance to collapse from external pressure considerably and the trend in recent years has been to provide slightly thicker linings or to introduce some means of anchoring the lining to the encasing concrete. In the case of the Clachan shaft the theory of Amstutz was of particular value in computing limiting pressures for the grouting of the lining.

In selecting the form of joints for the lining it was decided to use a type or types which would enable each joint to be pressure tested and passed as it was made, and before the encasing concrete was placed. Taking account of the working pressure and the site conditions, and the need for a dependable high standard of quality, it was decided that overhead welding should not be permitted for the main welds of site joints. Adopting the foregoing criteria, flanged joints with a double sealing ring were selected for strakes Nos 1 to 53 and welded joints having an outer cover strap to facilitate assembly for strakes Nos 54 to 87 (see Fig. 14a). The use of site-welded joints was thus confined to pipes subject to an internal pressure not exceeding 275 lb/sq. in. and overhead welding was eliminated by suitable arrangement of the Vee prepared for the welds, taking account of the steep slope of the shaft.

The steel lining was made up from plates approximately 8 ft wide, bent to radius and prepared for shop welding to form pipes 24 ft long. The meeting faces of the flanged joints were machined after welding. Each pipe was pressure tested at the maker's works. Because the lining is a composite construction the test pressure could not exceed the working value by the margin normally specified for steel pipe lines, but the pipes were subjected to a very rigorous inspection when under pressure and the engineers were satisfied that the test served its purpose since the stresses exceeded the calculated working stresses in the lining by at least 40%. The closing length immediately upstream of the station valve is tapered and incorporates connexions to the pipeline drain and to a number of plant auxiliaries. Having regard to the number and form of the welds and welded attachments to this pipe arrangements were made to have it annealed after fabrication.

Although the clearances within the shaft were defined as the practical minimum the joints were made without difficulty. The flanged joints were particularly successful and there were only one or two which did not pass the site pressure test at the first attempt.

The specification required that the concrete encasing the pipes should be poured in lengths not exceeding 50 ft. The concrete was delivered into position by pumping from the surge-pond area and it was found from preliminary trial runs that a mix with a $3\frac{1}{2}$-in. slump and a relatively high proportion of natural sand could be delivered through the long steeply inclined pumping main without risk of segregation, the friction being sufficient to offer considerable resistance at the pump. Immersion vibrators were used to ensure that the concrete surround was dense and well packed into the crevices in the rock.

The steel lining was provided with a liberal number of screwed plugs and, after a period of time to ensure that the concrete surround was thoroughly matured, pressure

routing was undertaken. Grouting pressures were defined for each zone having egard to the thickness of the steel lining, the aim being to fill any voids or fissures y injection of cement grout without risk of buckling the lining. For the $\frac{7}{16}$-in.-thick ipes a pressure of 25 lb/sq. in. was recommended, rising to 200 lb/sq. in. for the $\frac{5}{8}$-in.-nick pipes, which was the maximum pressure permitted. On approaching the zone f limited rock cover near the generating station the grouting pressure was reduced. s might be expected, the crown holes along the nearly level section close to the enerating station absorbed some grout (approximately 2·6 cwt/linear ft of tunnel) nd the invert holes also took significant quantities (average 0·2 cwt/ft), indicating nat the light-gauge rails used for skidding the pipes into position had tended to estrict the inflow of concrete to the space between the rails.

Grouting proceeded without incident until there remained only a short section etween strakes Nos 57 and 66 to complete. Injection was proceeding at strake o. 65 when there was a loud report at strake No. 67 and an extensive bulge de-eloped, as shown in Fig. 15. On investigation it appeared that the grouting ressure defined at the pump had been exceeded momentarily. Before further routing was undertaken a detailed examination was carried out and this revealed nat, upstream of the flanged section of the shaft, areas of the lining had a hollow-ounding ring when tapped on the inside These areas varied in size and position ut did not generally exceed about 10 to 15% of the peripheral surface at any section. oles were drilled through the lining at selected points and feelers were inserted to auge the clearance at the largest hollow-sounding zones. It was found that the earances were generally of the order of 1×10^{-3} in. with a maximum of 5×10^{-3} in. ince a significant rise in the temperature of the lining took place due to the heat berated on placing the concrete surround, it seemed clear from analysis that the earances could be explained mainly by contraction of the steel lining on cooling hile the concrete was immature, and partly by shrinkage of the surrounding con-ete. The general absence of hollow-sounding areas at the flanged section is xplained by the interlocking value of the flanges and the securing bolts which form very effective anchor with the surrounding concrete.

When the lining at strake No. 67 was damaged preparations were in hand for first-age commissioning to enable the Clachan generating station to be put into service nd the plant was urgently required to avoid load shedding at peak periods. It was erefore decided to secure the weak zone with two stiffening rings as shown in ig. 15 and commission the plant for use in the early months of 1955 on the under-anding that a proper repair would be carried out during the subsequent summer eriod when the output would be reduced on account of the relatively small catch-ent then developed and the limitation of the storage then available.

Arrangements were made accordingly and the Clachan plant was put into com-ercial service in January 1955. The tunnel system was dewatered about 6 months ter and revealed that the bulged portion had deformed still further, the maximum ojection into the shaft being about twice that shown in Fig. 15. A full repair was it in hand and, on cutting out the damaged portion, it was noted that an area of e original encasing concrete was fouling the replacement plates, suggesting that ere must have been a slight flattening of the pipe in that region, which together ith the excess grouting pressure would be sufficient to explain the occurrence cording to the theory of Amstutz. When the repair was being carried out it was oted that there was a trickle of water flowing into the region and there were indica-ons that on sealing this off the pressure built up. Having completed the repair a uge was fitted and readings up to 100 lb/sq. in. were recorded. This pressure

corresponds with the static head to the surface and was greater than might have been expected since the weather at the time was exceptionally dry, the drought conditions then prevailing being the driest recorded for many years. The action is clear from a study of the geological particulars shown in Fig. 14. The fissured

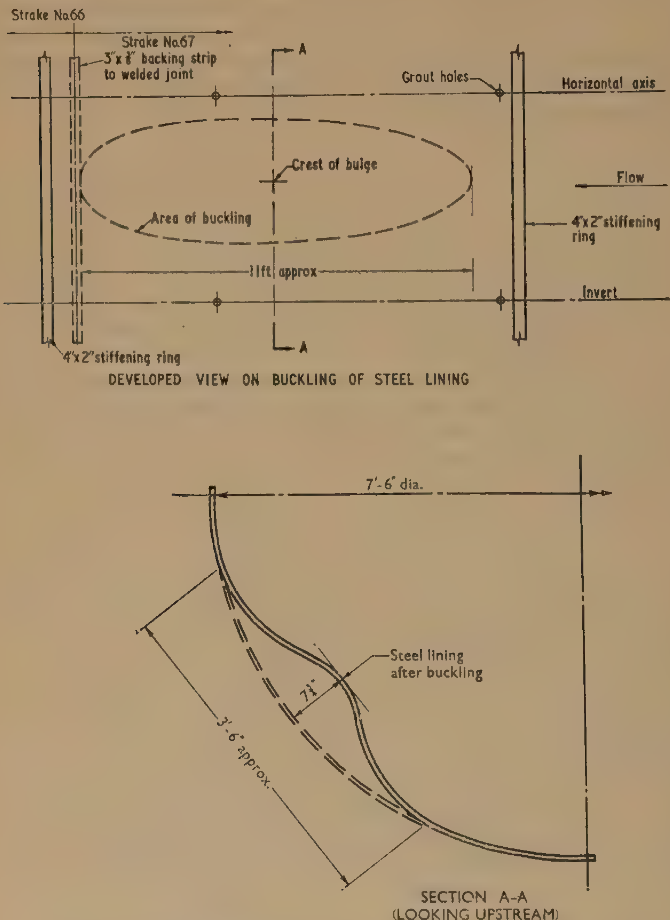


FIG. 15.—PRESSURE-SHAFT LINING—BUCKLING AT STRAKE No. 67

intrusion of epidiorite upstream of strake No. 67 permits ground-water to percolate to the quartz-schist zone downstream which, being more impervious, acts as a barrier causing a build-up of pressure equivalent to the static head to the ground surface.

The interior surface of the steel lining has been flame cleaned to remove deposits of rust and traces of mill scale and a four-coat paint protection has been applied. By applying the first priming coat to the metal in a warm condition the difficulties arising on account of the humid conditions in the shaft were largely overcome.

The surge shaft has an internal diameter of 20 ft and is concrete lined throughout. tails of the cross-section are given in Fig. 14, together with the main particulars the surge chambers. At the intersection of the main tunnel with the surge and essure shafts a lower chamber has been formed to cope with downward surges en the water level in the reservoir is low. In the design of this chamber and the rge shaft, the sections were proportioned to encourage the release of air entrained the water from the side stream inflow at the Brannie Burn. Since major diversions brought into the tunnel system through the surge pond and shaft the form of the et to the shaft also required special consideration.

Clachan generating station and related works

The Clachan power station is the first large underground station commissioned on Board's projects although there are several others at various stages of construc-n. The station accommodates one 40-mW generating set driven by a vertical-ft Francis turbine of 56,000 b.h.p. capacity at a speed of 428 r.p.m. under a gross ad of 960 ft. It is the largest capacity water-turbine-driven set so far installed in United Kingdom. The full-load demand of the turbine is 630 cusecs.

The general arrangement and principal details of the station are shown in Fig. 16, ate 2, and Figs 17, 18, and 19 (pp. 618–19) illustrate stages in the construction. The cavation above main floor level was carried out by quarrying methods, advancing m the cutting formed on the line of the access. The area around the generator was en excavated by sinking from floor level and broken through into the pilot tunnel pre-usly driven for access to the pressure shaft. As will be seen from Fig. 16, Plate 2, concrete walls of the basement section were poured hard against the rock. To clude dampness the inner faces of these walls are sealed with asphalt held in sition with a lining of brickwork. The reinforced concrete framework of columns d crane girders supporting the 150-ton overhead travelling crane has been anchored gitudinally and transversely into pockets cut in the solid rock of the main excava-ns. By this means a rigid crane gantry was provided at minimum cost. The in roof takes the form of a substantial reinforced concrete arch springing from ewbacks cut into the rock above crane-beam level, thus reducing the loading which normally supported by the crane columns. At the site of the station the rock, ich is quartz-mica-schist, dips to the west-north-west at 30 to 40° and includes ashed zones. The bedding planes on the downstream side were open-jointed and arge mass of rock in that region which became insecure on excavation had to be moved. To meet these conditions the span of the roof had to be increased as own in Fig. 16, Plate 2.

An inner lining of brickwork has been provided forming panels built between the ne columns, and a suspended ceiling of reinforced plaster hung from the main roof shown provides a continuous cavity between the internal structure and the cavated rock above main floor level. Circulation of air in the cavity is encouraged means of an opening through the roof of the access tunnel and by an air shaft ovided with louvre outlets above roof level. Adjustable louvred openings are ovided in the lower panels of the main entrance door and along both sides of the spended ceiling. The latter openings connect with the cavity in which there is a nsiderable natural movement of air, thus assisting in the ventilation of the station, ich is further encouraged when the plant is running by discharge of the warm air m the alternator at a point below main floor level on the upstream axis of the

machine. Further openings were formed to facilitate the installation of air-conditioning plant in the future, if necessary, but operating experience during the past year has indicated that the natural ventilation arrangements outlined above are quite satisfactory. Vermiculite plaster was used for the finish of the brick-panelled walls and the suspended ceiling to minimize any tendency there might be for condensation during periods when the atmosphere is humid.

On the advice of the Fishery adviser the tail-race was arranged to discharge into the River Fyne a short distance upstream of the point where the river enters Loch Fyne, since this would encourage breeding fish to enter the river. This arrangement, while shortening the main tunnel, involved the construction of fairly extensive tail-race works and several different forms of construction had to be adopted on account of the site conditions. Measuring downstream from the draft-tube gate shown in Fig. 16, Plate 2, these tail-race works comprise a concrete-lined tunnel 21 ft wide by 100 ft long driven in rock, leading into a section 150 ft long constructed in reinforced concrete by cut-and-cover methods. This latter connects with a concrete-lined channel 27 ft wide and 930 ft long leading to the outfall portion 600 ft long, which is of trapezoidal cross-section having a concrete invert and side slopes lined with random rubble pitching.

The methods adopted by the contractor in constructing the short length of tail-race tunnel may be of some interest. The pilot tunnel previously referred to formed the upper right-hand quadrant of the cross-section looking upstream. When the sinking of the generating station excavations had advanced sufficiently to enable the break-through to be made, thereby providing an alternative means of access to the pressure-shaft works, the upper portion of the tail-race tunnel was widened and trimmed to final profile. In view of the limited rock cover and the crushed condition of certain zones of the rock strata, steel arch-ribbing was introduced, the roof ribs having bearing plates at the skewbacks and bolted flange connexions to the uprights. When the installation of the roof ribs was complete the contractor followed with the lower portion of the heading, adopting a suitable drilling and blasting technique to avoid undercutting the skewbacks. The steel ribs, which were up to 24 ft high to the crown, were thus erected without the use of scaffolding (see Fig. 16, Plate 2, and Fig. 17).

Near the south-east portal of the tail-race tunnel the rock surface drops on a vertical face and the works downstream of this point had to be constructed through alluvial sand and gravel deposits and river ballast. The concrete-lined construction of the tail-race channel was adopted to suit the subsoil conditions in that zone, which comprise mainly running sand. This was encountered in the excavations about 6 ft above foundation level and the construction was carried out in sections without difficulty using shallow well-point dewatering methods. Since the ground-water table can rise up to 8 ft above foundation level, the cross-section of the channel had to be substantial to resist flotation and semi-mass construction was adopted, using a simple form to facilitate rapid construction, section by section, while the water-table was held down by means of the well-point equipment.

The hydraulic design of the tail-race works was checked by model tests carried out to determine the maximum height of waves occurring on sudden load rejection. From the findings of the model tests minor adjustments were made to the details, the height of the tail-race tunnel being reduced slightly, and the coping level of the open channel was raised a few inches.

The tail-race channel terminates on the west bank of the River Fyne where a fish screen is provided having square meshes, 2-in. clear, in the form of light removable

nels. Extensive model studies of this section were carried out to safeguard the posite bank of the river which has been heavily eroded by occasional spates for me years past and it was desired to ensure that this condition is not aggravated by e discharge from the generating station.

The control room and administrative offices are not housed in the underground ction but form the main apartments of an adjoining outdoor building alongside the itching station. The generating plant, both in the Clachan and Sron Mor stations, remote controlled from the control room, the power and relay cables and other rvices to the underground station being accommodated in a duct which follows the ne of the access into the station.

The station transformer is located alongside the entrance portal and is screened om general view by the control-room building. The output is fed by 132-kV erhead lines to the Inveruglas switching station of the Loch Sloy hydro-electric oject, about 10 miles distant.

Diversion aqueduct works

Having regard to the high head and the intensity of rainfall on these upland areas, e extensive diversion of water from adjacent catchments forms an attractive ldition to the scheme.[1] These diversion works comprise free-flow tunnels, con-ete-lined aqueducts, and (for the smaller streams) piped aqueducts.

It is usual to design such works to accommodate $4\frac{1}{2}$ to 5 times the average flow. ne latter figure was adopted for the Shira scheme and a freeboard allowance has en introduced. Some sections which are short and relatively inexpensive have en designed to deal with flows up to 10 times the average.

The diversion works can be broadly considered in two sections, namely:

(1) those which feed into the lower reservoir principally through the main tunnel system; and

(2) those which feed into the upper reservoir.

ne main particulars of the diversions are given in Table 3 and, since the works nerally follow accepted practice, only matters of special interest are referred to.

Spun-concrete pipes have been adopted as representing the most economic form construction for waterways up to an equivalent diameter of 42 in. Pipes having tented flexible joints are used with advantage, the joints being easily formed spite the wet conditions prevailing and permitting an angular deviation of about to be made where necessary, thus reducing the depth of excavation on many ctions where the hillside is in the form of a series of curved ridges. For the larger ueducts constructed along the hillsides, in-situ concrete construction has been lopted using a trapezoidal section with the width approximately twice the depth d having the side walls battered at 1 horizontal to 2 vertical. Maintenance of en aqueducts on these exposed sites can be onerous during periods of snow and ost and the in-situ sections on this scheme are being covered over with factory-ade prestressed concrete slabs spanning between the side walls.

During spates considerable quantities of debris may be carried downstream in ese Highland burns and a preliminary reconnaissance of the terrain indicated that e drift would probably be heavy since extensive areas of the hillsides traversed ve a covering of moraine overlying the rock. To meet these conditions, it was cided that the stream intakes should not take the usual form with a bar screen ounted on the upstream face of the dam or on the side approach to the intake and

TABLE 3.—DIVERSION AQUEDUCTS

Section		Catchment area: sq. miles			Design flow: cusecs		Form of construction	Total length (of aqueduct): ft	Total length (of aqueduct): miles
Main reservoir	Direct catchment	4·59	4·59		—				
	Diverted from:								
	River Fyne area (Nos 3, 4, and 5)	4·8			199		18-in. to 33-in. pipes, 6-ft × 4-ft channel, 6-ft-6-in. × 6-ft-6-in. tunnel	20,540	3·88
	Allt-an-Stacain (No. 6)	1·84			53		3-ft-9-in. × 3-ft-0-in. channel	6,060	1·15
	Allt-an-t'Sithein (No. 8)	2·14	8·78	13·37	58	310	15-in. to 27-in. pipes, 3-ft-9-in. × 3-ft-0-in. channel, 5-ft × 6-ft tunnel	7,770	1·47
Lower reservoir	Direct catchment	0·6	0·6		—				
	Diverted from:								
	Beinn Ghlas (No. 7)	1·35			39·6		18-in. to 36-in. pipes	9,360	1·77
	Brannie Burn (No. 10)	3·73			189		18-in. to 30-in. pipes, 6-ft × 4-ft channel	7,350	1·39
	Kilblaan Burn (No. 11)	1·59					21-in. pipe, 5-ft × 6-ft tunnel	7,530	1·43
	Clachan area (No. 11)	0·85	7·52	8·12	136·2	364·8	30-in. pipe, 5-ft × 3-ft-6-in. channel	4,030	0·76
	Total .			21·49					11·85

.e problem was studied in detail with a view to developing some form of self-eansing screened intake or, alternatively, a screenless type of intake.

Fig. 20 shows the typical design adopted for the intakes on small streams incor-orating a self-cleansing screen, the bar screen being mounted on the overfall or ownstream face of the spillway. The spillway is stepped as shown, so that nor-ally the flow is directed through the screens. During flood periods part of the flow rejected over the flood crest while the high flow passing over the inlet crest is fective in clearing the screens of any debris which may have accumulated. On the ped sections where site conditions permit, the intake dam is formed on the line the aqueduct and serves as a surround to the pipes to secure them in position at .e stream crossing. Several of these intakes have been in service for the past ason and have performed very satisfactorily, the screens requiring practically no tention from the maintenance staff.

The details given in Fig. 21 illustrate the layout of a major stream intake which s been constructed without screens, a baffle wall being used to divert river debris ear of the inlet channel. In this design excess flood water passing over the inlet est is rejected by means of a projecting nib which divides the nappe when the flow ceeds the selected value. Construction of one of these intakes is now well advanced d it is hoped to commission this section within the next few months.

Both of these designs were improved by hydraulic model studies and were the bject of a Student's Paper submitted in competition for the Institution Medal in 954.[7] It was realized in developing these designs that a high degree of precision uld not be expected in controlling the rejection of excess flood water since the rformance would be affected by any accumulation of debris or by the intensity d direction of the wind. Accordingly, the intakes have been generously propor-oned to bring in rather more than the design yield and relief spillways have been ovided to reject surplus water which would surcharge the system if passed down-ream. Apart from the performance of the intakes, such an arrangement is voured to deal with the variable distribution of rainfall which, according to ex-rience, is by no means uniform throughout the length of an aqueduct even on ese small catchments, and to ensure that the capacity of the aqueducts is effectively ed it is desirable that the individual intakes should be designed to bring in more an their theoretical proportion.

As will be seen from Table 3, the Brannie Burn diversion, which is fed into the ain tunnel midway between the lower reservoir and Clachan, is designed to deal th flows up to a maximum of 189 cusecs, which is nearly one-third of full-load w. The Kilblaan and Clachan Burn diversions, which are fed into the tunnel stem through the surge shaft, deal with a maximum flow of 136 cusecs. It is portant to ensure that entrained air in significant quantity is not allowed to pass wnstream to the turbine in case cavitation should result with consequential oubles. Instead of the siphon intakes introduced on some schemes to obviate ese difficulties, a simpler solution was sought for the Shira works. This course as favoured because the provision of siphons and their ancillary works, for the large ws involved, would have added considerably to the cost, particularly since very fective measures would have been necessary to exclude debris during flood periods. xperiments were conducted to study the behaviour of water flowing down a steeply clined shaft proportioned in such a manner that at least one-third of the cross-ctional area is available for air release. The release of entrained air by the pro-sion of an expansion chamber arranged to form part of the surge relief works was so studied. The scheme finally adopted is on very simple lines, comprising a

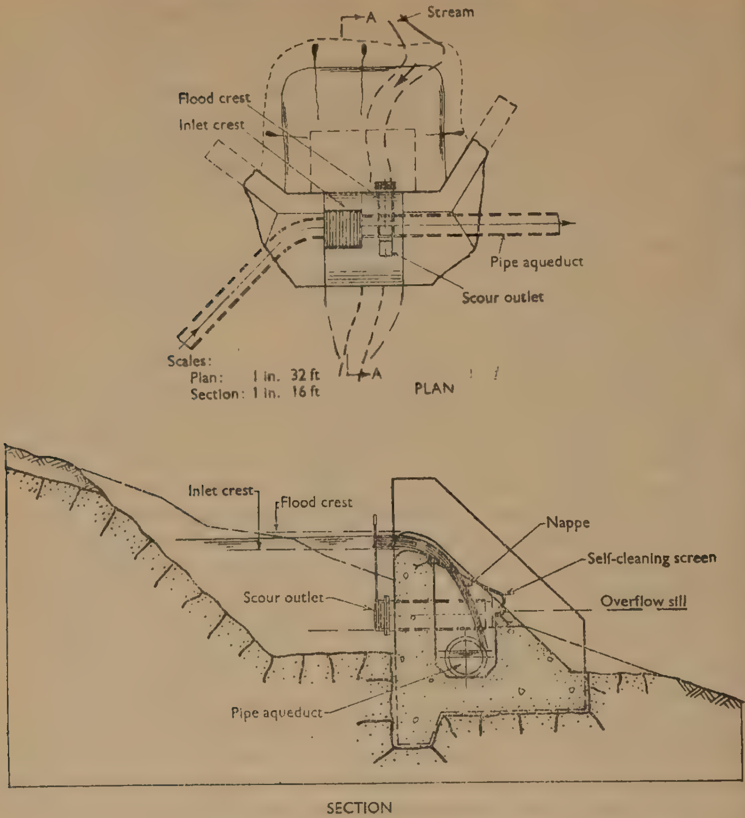


FIG. 20.—TYPICAL SMALL STREAM INTAKE

48-in.-dia. steel pipeline laid at an average gradient of 1 : 6·4 for feeding the Branni diversions into the tunnel system and an enlargement of the tunnel at the foot of th surge shaft to form an expansion and surge gallery for release of entrained air throug the inclined surge shaft. These works have been in commission for several month and have performed satisfactorily in the manner envisaged.

GENERAL

About 15 miles of access roads were required to serve the works and some section had to be constructed through rough sidelong ground where the stability of th moraine overlying the steeply inclined surfaces of the rock is disturbed by th excavation of cuttings, even although these are relatively shallow. The progress o these sections was slow in consequence and the roadworks occupied a period of almo 18 months before an effective start was made with other main sections of the schem in the spring of 1950.

To meet the constructional requirements, which amount to fully 500,000 tons c aggregate, an outcrop of epidiorite situated about half a mile from the site of th

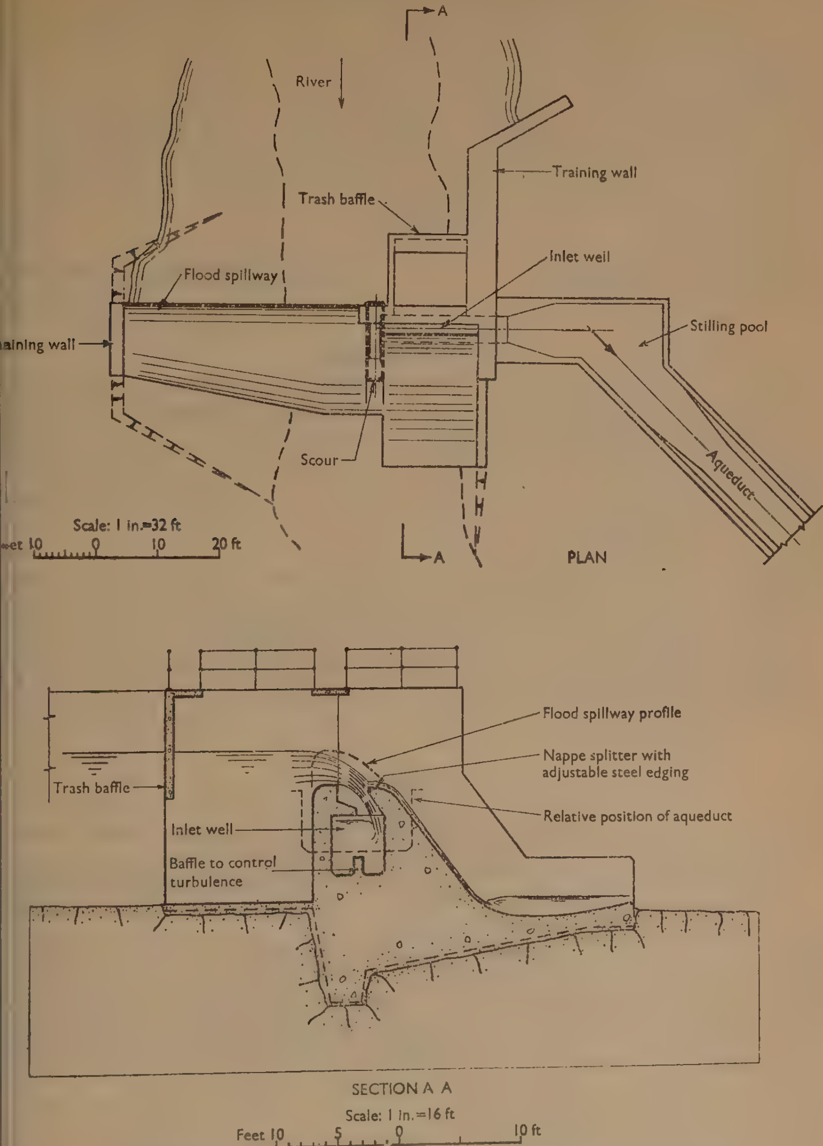


FIG. 21.—TYPICAL MAJOR STREAM INTAKE

in dam was opened up and quarry plant formerly used at the Board's Loch Sloy ject was modified and installed. Since the nearest source of supply of natural d is about 45 miles away the quarry plant is operated to produce a large output rock sand. The installation[8] is capable of a daily production of 1,000 to 1,200 s of separate-sized washed aggregates.

A military camp established during the 1939–45 war was taken over and re equipped to accommodate up to 1,000 workmen and a peak labour force of abou 800 has been employed on the site each season.

The civil engineering works were subdivided into three main contracts and put ou to tender at one time so that the contractors quoting were in a position to offer fo the whole works if they so desired. The combined tender submitted by A. M Carmichael Ltd, Civil Engineering Contractors, Edinburgh, was accepted. Th main contract for mechanical and electrical plant was awarded to the Englisl Electric Co. Ltd.

The estimated value of the whole works, including generating plant and trans mission lines, is £7 million.

Acknowledgements

The Consulting Engineers for the civil engineering works of the project are Messr Babtie, Shaw & Morton, and for the mechanical and electrical works, Messrs Mer and McLellan. The scheme as designed conforms with the original conception of a two-stage layout proposed by the late Mr James Williamson, M.I.C.E., who was associated with the development in his capacity as a member of the Board's pane of technical advisers.

The Author is indebted to the North of Scotland Hydro-Electric Board for per mission to publish the information given in this Paper and desires to express hi thanks to Mr A. A. Fulton, B.Sc., M.I.C.E., F.R.S.E., General Manager of the Board for helpful suggestions particularly with respect to the plant installations. Thank are also due to Mr W. Hamilton, B.Sc., A.M.I.C.E., Mr G. Rocke, B.Sc., A.M.I.C.E. and Mr N. G. Semple, B.Sc., A.M.I.C.E., of Babtie, Shaw & Morton's staff for thei assistance in the preparation of the Figures.

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The Paper, which was received on 16 January, 1956, is accompanied by seve photographs and fourteen sheets of drawings, from which the half-tone page plates folding Plates 1 and 2, and the Figures in the text have been prepared.

THE GLEN SHIRA HYDRO-ELECTRIC PROJECT

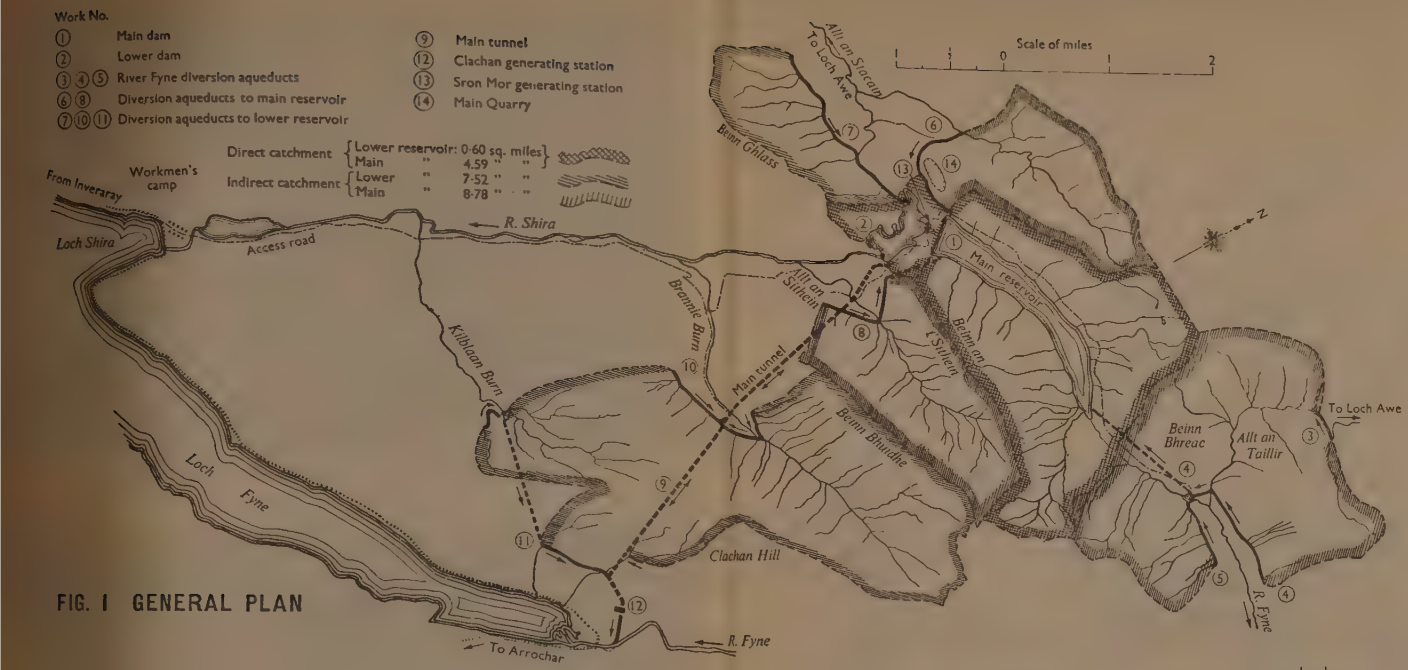

FIG. 1 GENERAL PLAN

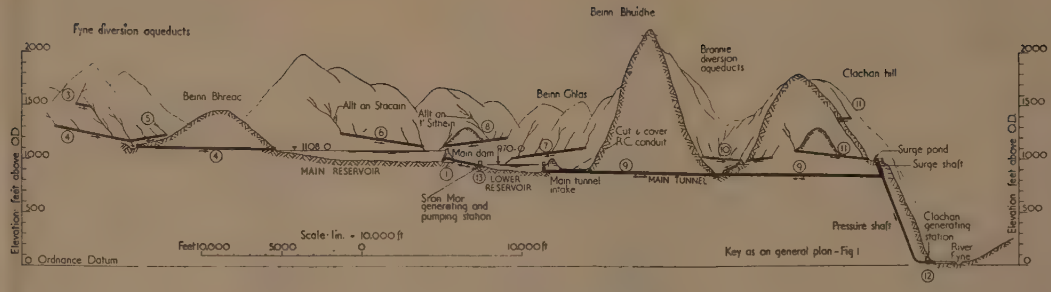

FIG. 2 HYDRAULIC SECTION

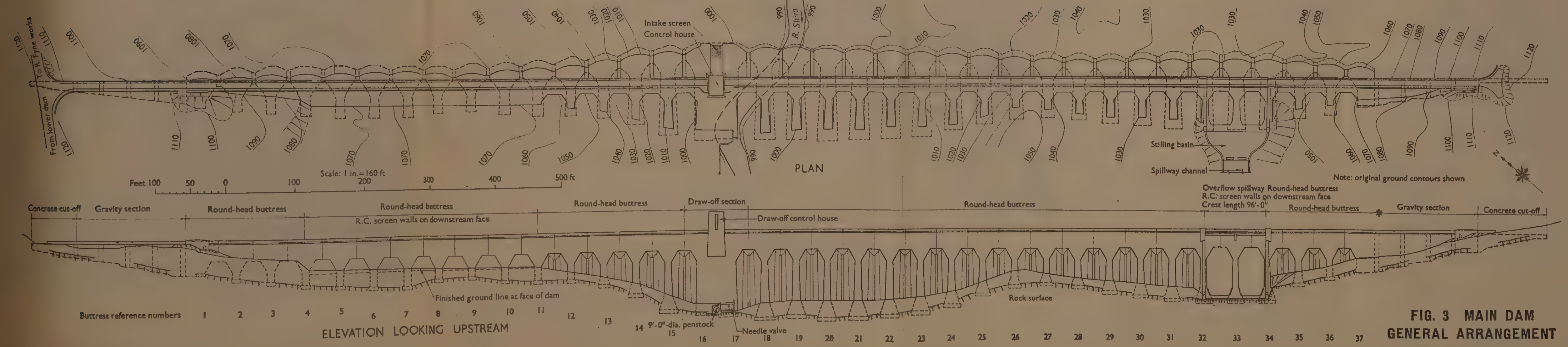

FIG. 3 MAIN DAM GENERAL ARRANGEMENT

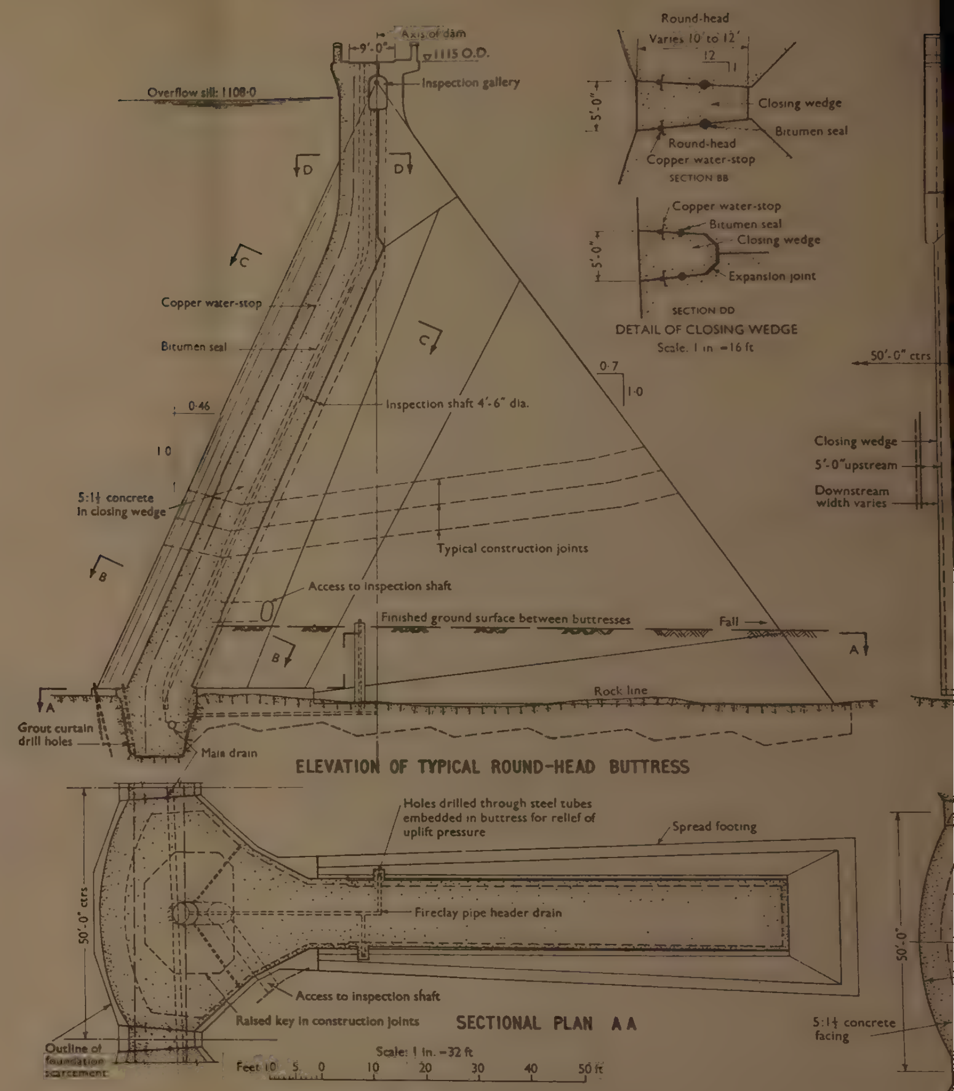

FIG 4. MAIN DAM—DETAILS OF TYPICAL ROUND-HEAD BUTTRESS

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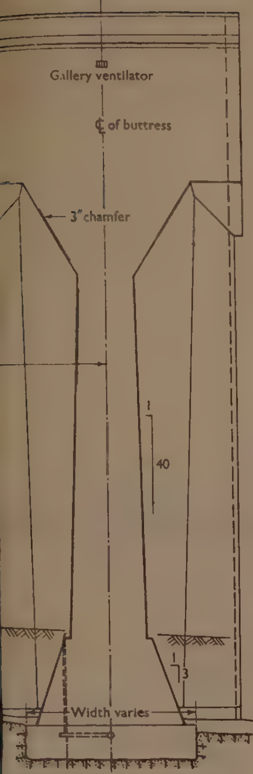
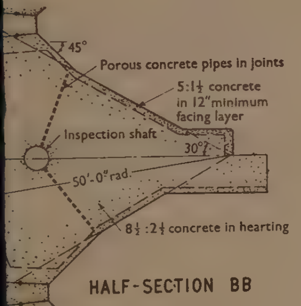
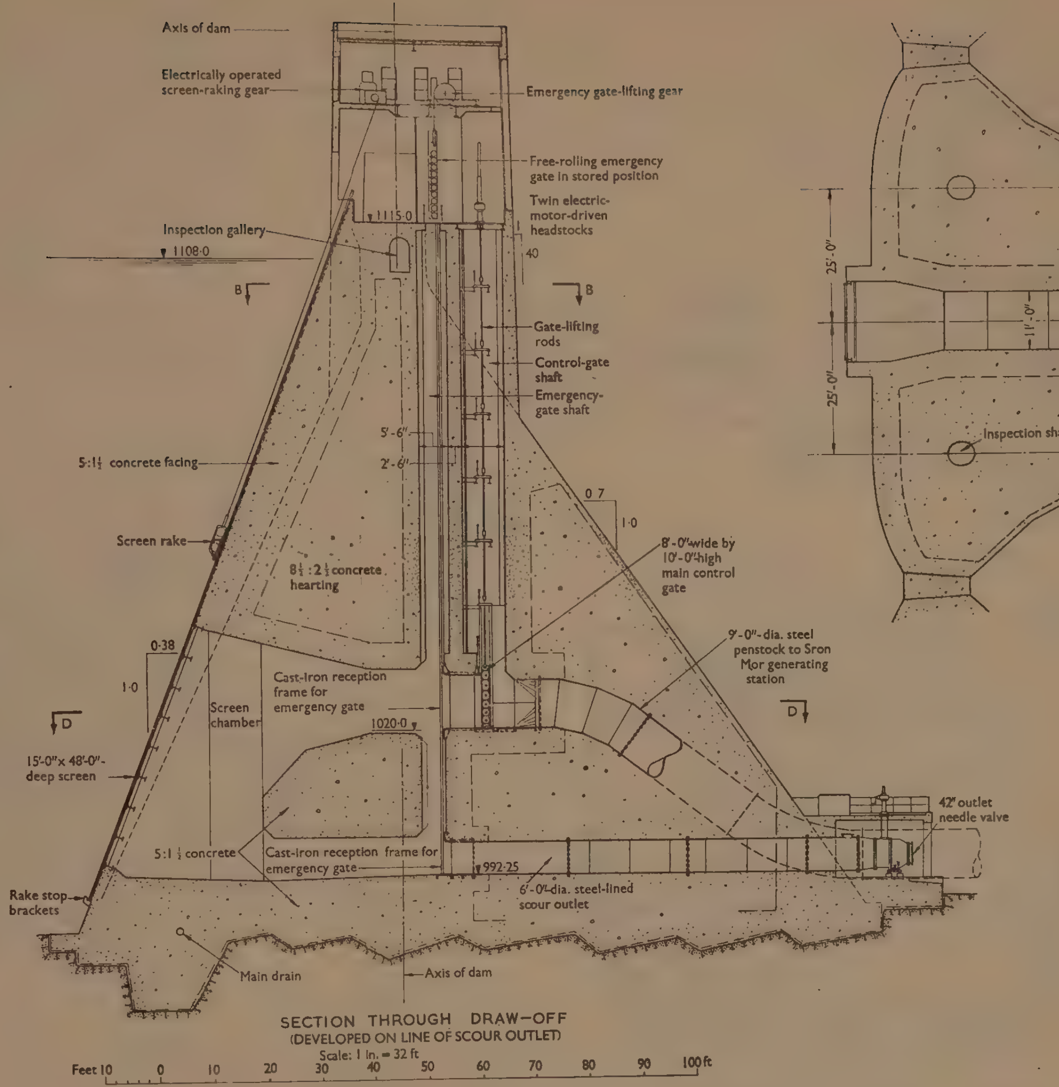


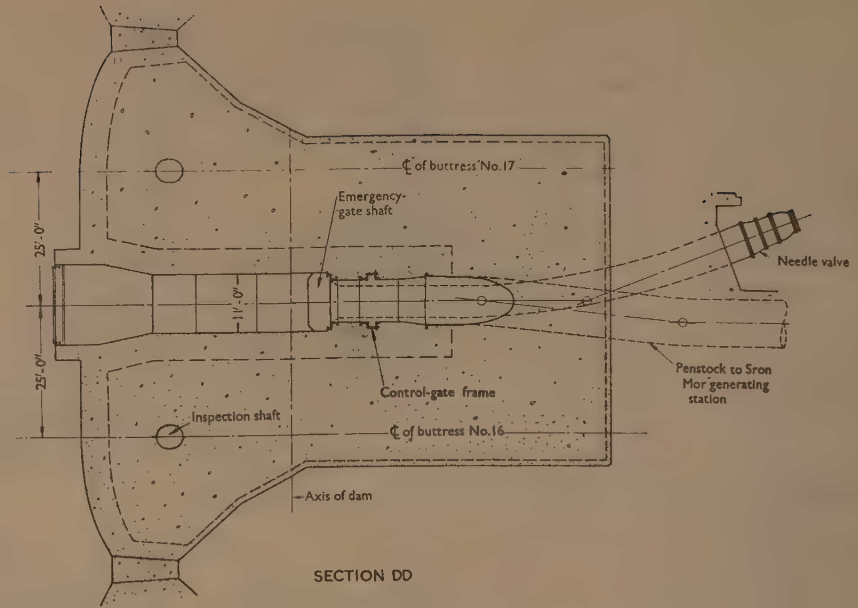
DOWNSTREAM ELEVATION



HALF-SECTION BB



SECTION THROUGH DRAW-OFF
(DEVELOPED ON LINE OF SCOUR OUTLET)
Scale: 1 in. = 32 ft



SECTION DD

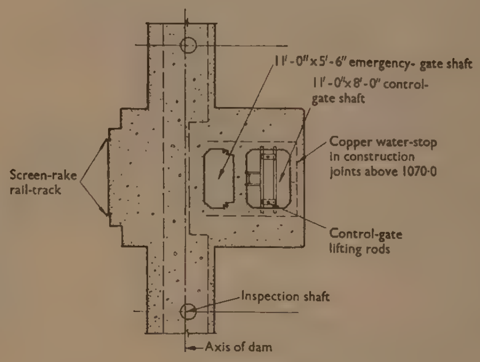


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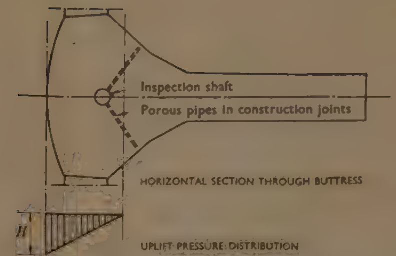
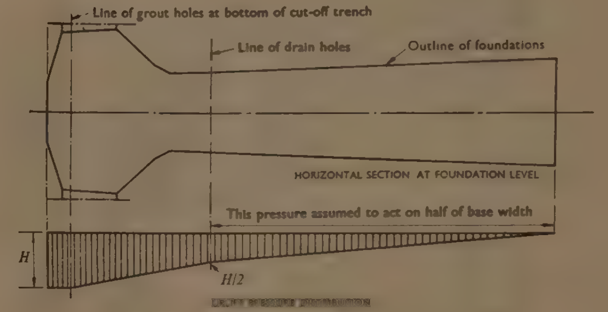
FIG.5 MAIN DAM. DRAW-OFF SECTION OF DAM



UPLIFT PRESSURE IN CONCRETE OF DAM



UPLIFT PRESSURE DISTRIBUTION UNDER FOUNDATIONS OF DAM

FIG. 9 DIAGRAM SHOWING UPLIFT PRESSURES ASSUMED FOR DESIGN OF ROUND-HEAD BUTTRESS DAM

JOHN PATON

Fig. 13.—General view of lower dam (Jan. 1955)

Fig. 17.—Clachan generating station. View from tail-race tunnel showing draft-tube shutter and pressure shaft

FIG. 18.—CLACHAN GENERATING STATION. INTERIOR VIEW LOOKING TOWARDS UNLOADING BAY

FIG. 19.—CLACHAN GENERATING STATION: CONTROL ROOM, ENTRANCE PORTAL, AND TAIL-RACE

Discussion

The Author introduced the Paper with the aid of a series of lantern slides.

Mr A. A. Fulton (General Manager, North of Scotland Hydro-Electric Board) said that it would have been gathered from the Paper and from the Author's description that the individual hydro-electric schemes in Scotland were of an interesting variety and on a substantial scale. On the civil engineering side alone, work to the value of £84 million had already been carried out since the war. Associated with that there had been expenditure on plant of £10 million, on transmission of £11 million, and on distribution of £30 million. Almost all of that work had been done and supervised by consulting engineers, so that, although split up into units and spread over several consultants, the field in Scotland for engineers and contractors was something approaching in value the much-publicized High Aswan Dam project.

It was a good thing that details of such work as was embraced by the Shira scheme would be recorded in the Proceedings. Much of the interesting work of a hydro-electric scheme was covered over or otherwise rendered inaccessible by inundation and flooding, and so, unless it was fully written up, some valuable lessons were bound to be lost.

The Shira scheme was not "just another hydro-electric scheme". It had an individuality of its own. It was a two-stage scheme, and, as the Author had explained, that was inevitable. It meant, however, that its operation would require more co-ordination and attention than would have been the case if it had been an orthodox conventional single-stage station. It had been made even more complicated by having pumped storage associated with the upper stage. It was the first real example of that in the United Kingdom. From its nature, its use would probably be quite limited. It was not intended to be anything other than experimental, and it would have its greatest value in a wet year.

The Author had explained that Shira was another good example of the extent to which diversion from adjacent catchments had been practised in schemes where heads were high and water was valuable. The Author had quoted the figure of 21·5 sq. miles of catchment area utilized as compared with only 5·2 sq. miles of natural catchment, which represented a proportion of about 24%. That compared with just over 20% for the Sloy scheme.

Like Sloy, Shira had a relatively low load factor, and in a year of average rainfall it would only have water to run at full load for about 2,000 hours. It would operate in association with the Sloy station, with which it had, as he had explained, many features in common. Its main generating set would be treated more or less as an extra unit in the Sloy station and was, in fact, for all practical purposes almost a duplicate of the Sloy machines.

The dams and the sloping pressure shaft, to which the Paper devoted particular attention, were the highlights of the scheme. Whilst it was always interesting to have new problems to face, Mr Fulton doubted very much if, in solving amenity problems by putting a pipeline underground and in cutting down cement requirements by using a buttress dam, the new problems of making up one's mind how much external pressure one had to allow on the lining of the pressure shaft or where all the carpenters for shuttering the dam were to come from, were not just as troublesome.

The wide variety of the work covered was impressive. There were three varieties of dam, and if that was not enough, there were side-stream intakes, free-flow tunnels, pressure tunnels, pressure shafts, collecting aqueducts (both open and closed), a substantial tail-race canal, and an underground power station. Those had given opportunities for experience and training for the many young engineers who had had the good fortune to work on the scheme.

The works would stand as a permanent monument to the care and diligence which he knew had been employed by the Author and by all those who had been associated with him. They had done a good job.

42

Mr J. A. Banks (Partner, Messrs Babtie, Shaw and Morton, Consulting Engineers) commented on the merits of the earth dam for the lower reservoir. Puddle-clay cores commonly associated with earth dams, although perhaps less frequently so in recent designs, were an inevitable source of weakness on account of the low shear value of the puddle clay and also the difficulty of achieving adequate compaction of the embankment materials adjacent to the core. Those objections had been overcome in the case of the Glen Shira project by adopting a reinforced concrete core, and the thin flexible section of the core wall ensured that positive advantage could be taken of the passive resistance of the compacted earth work. To provide flexibility without cracking, it had been necessary to put a heavy proportion of steel in the core. The reinforcement amounted to fully 3% by volume as compared with the volume of the concrete. The combination of bars and fabric had been found, by tests carried out on slabs, to give the most favourable arrangement of reinforcement for minimum cracking with maximum permissible deflexion.

The importance of avoiding any plane of weakness was the greater in the case of the Glen Shira project because of the rapid draw-down in water level. In a normal water-supply reservoir the rate of draw-down might rarely exceed a few inches per day, whereas the lower Glen Shira reservoir could be emptied in the course of a few days. Had a puddle-core wall been incorporated in the embankment, then the slopes, particularly upstream, would have had to be much flatter to lengthen the path against shear failure, with a consequent corresponding increase in the volume in the embankment, and that would in any case have been difficult because the site conditions limited the permissible base width of the dam. The concrete core had preserved the structural strength of the dam with economic advantage.

Preliminary designs indicated that an earth dam would be cheaper, showing a saving in cost of about 20% as compared with a concrete gravity dam, but it should be remembered that, in practice, an apparently substantial saving in one section of a project might not be fully realized when the works as a whole were taken into account. The Author had pointed out that, whilst the embankment had been raised at the rate of about 12 ft/month in reasonable weather conditions, progress had dropped to less than 2 ft/month when the weather was adverse. If, as so often happened, the material readily available on a site for the construction of an earth embankment had a very low or negligible frictional value, so that its strength was radically affected by change in the moisture content, then the rate of progress in constructing the embankment might be so slow as to affect progress with the works as a whole. The economic advantage of the earth dam was not materially affected in the case of the Glen Shira project, but it was obvious that the possibilities of delay in construction should be kept in mind in preliminary analyses of what might be the most economic form of dam in a particular case.

With regard to the grouting of the foundations, the quantity of cement required to provide an impervious cut-off on the Glen Shira site was surprisingly, almost astonishingly, small. In the lower dam, where the formation comprised phyllite with occasional bands of igneous rock, the quantity of cement injected amounted to 1·2 lb/sq. ft of curtain area. At the main dam, where there was a complex rock structure, ranging from soft phyllite and quartzite to limestone, the quantity of cement required was even less, averaging 0·67 lb/sq. ft of the grout curtain.

He had compared those figures with other works where the geological conditions were different, and he had found that in one instance, with a cut-off in sandstone, the quantity of cement injected amounted to 57·3 lb/sq. ft, and in another instance, where the formation consisted of volcanic ash with bands of somewhat shattered whinstone, 36·2 lb/sq. ft of cement were required. Those comparative figures indicated the uncertainty of forecasting in advance what provision it was necessary to make by way of cementation to provide a watertight cut-off. Both the extent of drilling and the quantity of cement varied over a wide range. In the two comparative instances given, primary, secondary, and tertiary holes with 5-ft spacing were required, whereas on the Shira site only at a few local points was drilling closer than 10 ft found to be necessary.

Mr J. Guthrie Brown (Partner, Sir Alexander Gibb and Partners, Consulting gineers) confined his remarks to that part of the Paper dealing with the buttress dam. As in the case of the Author, his firm had for some time been engaged in the design of eral of the major hydro-electric works being carried out in the North of Scotland. As back as 1944, his firm had had to give consideration to the best form of design for the rochty dam (part of the Tummel-Garry project) which was to be founded on rock at st as bad as that at Shira. Mr Banks had stated that the amount of grout absorbed in cut-off curtain at Glen Shira had been 0·67 lb/sq. ft. At Errochty the grout absorbed the cut-off curtain was 8 lb/sq. ft—12 times that at Shira.

The foundations for the Errochty dam consisted mainly of heavily shattered mica- ist, quartz-schist and horneblende-schists with veins of soft sandy clay at intervals at end of the dam. For those reasons, a maximum foundation stress of 7½ tons/sq. ft been chosen as compared with 10 tons/sq. ft for Shira.

Investigation of the different types of dams possible for such a site had led him to the me conclusion as the Author's, namely, that a buttress dam was the most suitable and onomical, connecting with a gravity dam at each end as the height of the dam reduced. e ratios of relative economy at which he had arrived were almost identical with those oted by the Author, namely, rock fill 1·4, gravity 1·2, and buttress 1.

The Errochty dam, like the Shira dam, was 130 ft high, but it was slightly shorter, cessitating the use of twenty-eight buttresses only compared with thirty-seven at Shira. th dams, it was interesting to note, were being constructed by the same firm of con- ctors. Errochty dam, however, was the earlier in design and was more advanced in nstruction.

One major difference was that the spacing of the Errochty buttresses was 40 ft compared h 50 ft at Shira, and they were diamond-headed buttresses instead of the round-head pe. He did not agree with the Author's reasons for adopting the round-head type and s still satisfied with the choice of the diamond-headed type. In the case of two other ttress dams at present under construction, one in Eire and the other in Scotland, both d adopted diamond-headed types of buttresses similar to the Errochty design. There- e, if he had sinned, he seemed to be in good company.

One point of criticism on the Shira dam was the wedge-shaped closing section, about t wide, between buttresses. Whilst that might have certain advantages, it had the ious disadvantage of doubling up the number of water seals and possible leakage paths. Errochty, the buttress heads abutted closely together, providing greater structural lation for individual buttresses as compared with the Shira type. In the case of rochty, a restriction of 2 months had been placed on concreting against existing but- sses so as to minimize the risk of too great a contraction opening. That had not held construction to any appreciable extent, and it had been entirely satisfactory.

After full consideration, it had been decided that no inspection shaft should be provided the centre of the Errochty buttress heads. The shaft had advantages during the cooling ge and for inspection, but it was considered by some to have objections from the point view of artificially steepening the pore-pressure gradients. Since both Errochty and ira dams were designed for a very high uplift, the shaft would not seem justified solely a means of easing uplift conditions.

The Author had not made any reference to deflexion measurements during the filling of reservoir, for which fairly elaborate provision had been made at Errochty. It would interesting to know whether any such arrangements were contemplated.

Mr Guthrie Brown then showed a series of slides illustrating the points he had made garding the comparisons between the Errochty and Shira dams.

Dr Charles Jaeger (Consulting Engineer, English Electric Co. Ltd, Rugby) said at the Clachan power station of the Glen Shira hydro-electric project was the first derground power station built in Scotland. It was noteworthy that the designers of project had shown such confidence in that very new design as to adopt it straightaway a 56,000-h.p. station. Because of the success of that type of construction, it had been

used for the design of other power stations belonging to the North of Scotland Hydro-Electric Board and also for many projects overseas where British consultants and manufacturers were involved.

A project such as that at Glen Shira required great versatility from the designer. Two dams of modern and difficult design, a large surge tank, a steel-lined pressure shaft, an underground power house, and a huge pump were some of the most interesting features of the scheme. Each of those items required special knowledge and great skill, and the design had to be backed by extensive investigations.

One particular example would serve to show the type of information which was required to finalize one detail of the design.

The tail-race tunnel was a free-flow tunnel. It was not desirable for such a tunnel to be suddenly put under pressure unless the tunnel was specially designed for such changes in the type of flow. When the turbine gates were opened and the discharge rapidly increased from no-load conditions to full-load conditions, a translatory wave was created in the canal caused by a sudden change in the rate of discharge. The height of such a wave could be predicted.

When the turbine closed and the relief valve opened simultaneously, the discharge did not vary, but the momentum of the flow suddenly increased widely. What was the effect of that change of momentum? The designers of the Glen Shira project thought that problem should be investigated on a model.

Fig. 14a gave the general arrangement of the power house, the tail-race tunnel, and the tail-race canal. Further details showing the turbine draft tube and the relief valve were shown in Fig. 16, Plate 2.

Fig. 22 showed the general arrangement of the tests carried out in a model canal at Rugby. The pumps A, the pressure equalizer C, and the three-way cock H directed the flow towards the model draft-tube J or towards the relief valve K. L represented the tail-race tunnel and M the tail-race canal.

The canal model had been made to scale and the roughness had been calculated in accordance with the scale.

Fig. 23 showed the main test results. Curve (a) represented the wave in the tail-race tunnel and the tail-race canal when the turbine was opening from 0 to 630 cusecs in 20 sec. Curve (b) represented the case with the turbine closing with the relief valve opening in 2 sec, the flow being 630 cusecs. In that case the discharge was constant, but the momentum was increased. It could be seen that the translatory wave height created in that case was far greater than that created by the ordinary condition when the turbine was opening. Finally, there was the emergency condition when the relief valve suddenly opened in 2 sec. In that instance there was the highest possible wave in the canal. Fig. 23 showed the first level for the tail-race tunnel soffit, and the revised design based on the tests.

The examples which Dr Jaeger had shown were taken from a Paper by Adler[9] which illustrated the type of detailed research work on which the design as a whole was based.

Mr P. L. Blackstone (Head of Hydro-Electric Department, Messrs Merz and McLellan, Consulting Engineers) said that the single machine at Clachan power station had, as the Author had mentioned, the highest designed output of any on the Board's system, being 40,000 kW. It was not physically the largest machine; the turbine itself was actually the same as the turbines at Loch Sloy, but with a different runner design to suit the slightly larger head. The size of the runner at Clachan (5 ft dia.) was almost the same as that at Sron Mor, which produced 5,000 kW. In other machines on the Board's system there were runners of about 10 ft dia. It was a conventional vertical Francis turbo-generator.

The plant at Sron Mor included an induction generator of 5,000 kW output—one of th

9. G. F. W. Adler, "Model Tests on Clachan Underground Power Station." English Electric Journal, vol. 11, No. 4, June 1950.

rgest in the world. The induction generator had certain disadvantages. It caused a rly large surge on the electrical system when it was switched on, and it had, of course, be run on an inter-connected system because it had to be supplied with its magnetizing rrent from synchronous machines. Therefore, it was applicable only to an inter-nnected system, but provided that there were not too many in the system, it had some vantages.

The turbine required no governor because there was no close speed control required an induction generator. It was much simpler, and probably in the long run the main-nance of the machine would be less than with a conventional synchronous machine.

The difference in cost between an induction generator and a synchronous generator for on Mor had been closely investigated. It had seemed that there would not be much fference for the capacity involved. For smaller capacities the induction generator peared to be cheaper than the synchronous generator, but that advantage was reversed en the machine became much larger in capacity than that in question. It was difficult say where the dividing line should be because designs had not been developed for very rge induction generators.

The original idea had been to have the Sron Mor station at the foot of the dam; in that se a synchronous machine would have been quite suitable, but later it had been decided move it down-stream—as would be seen, the pipeline was about 700 ft long—and rbine regulation would have been difficult if a synchronous generator had been adopted. or that reason, among others, the decision had been made in favour of the induction nerator. It was quite a novel feature of the station, but the Board was now introducing me others of a smaller size on its system.

Sron Mor station was entirely automatically controlled—a feature which is particularly sirable for stations built in intractable country, as that area was in winter. There ould, of course, be local manual control in emergency.

On the remote control panel at Clachan there were five controls for the Sron Mor plant. here was a button which would start the turbine, a button to start the pump, a stop utton, a button to control the output of the machine (which was done by electric drive of e guide vanes of the turbine), and a switch to open and close the generator breaker.

Pressing the turbine start button automatically started the auxiliary plant. It used the turbine spiral casing to fill with water, and at the same time it emptied the ump casing of water by means of compressed air. When those operations had proved emselves electrically, the operator could then open the turbine guide vanes by means the output control and run the machine up to synchronous speed. He could then close e machine on to the system and with the output control load it up to whatever load he anted. It was all just as simple as that.

If the operator wanted to pump, all he had to do was to press the button marked pump start." That set in motion a different sequence of events. It started the turbine st in order to get the machine rotating at synchronous speed before it was switched on the system, so reducing switching surge; the pump was primed by means of an injector; e operator closed the generator on to the system; and the pump valve then automa-cally opened. The whole operation was done by the pressing of one button.

The control was by direct wire and the alarms and indications were taken back to lachan power station by supervisory equipment working over pilot wires carried on the ter-connecting 33-kV power line between the two stations.

Fig. 10, Plate 2, showed that the machine incorporated a flywheel. It was one of the sadvantages of the induction generator that it had little flywheel effect. The flywheel as required not for the regulation of the turbine but for the pump. If the motor was riving the pump and the supply was tripped because of a fault developing, the water olumn which was going up the pipe would stop and then reverse and drive the pump as a urbine. That might lead to serious waterhammer effects.

The machine had a rigid coupling between the generator and the pump. It was common ractice with pump storage plants on the Continent to have either a mechanical or a ydraulic coupling so that the pump could be disconnected from the machine very quickly

and so avoid losses which would otherwise occur when generating by driving with the pump either in water or in air. It was not considered necessary at Sron Mor to incur the expense of having such a coupling, but provision had been made so that if it was anticipated that the pump would not be used for a long period, the rigid coupling could be disconnected by putting jacks on to the flywheel and moving the shaft of the pump slightly longitudinally. By that means, a saving of about 1% was made in the losses which would occur when driving the pump.

Dr L. F. Cooling (Head of the Soil Mechanics Division, Building Research Station, D.S.I.R.) referred to the pore-pressure observations on the earth embankment of the lower reservoir. As stated by the Author, the dam was likely to be exposed to rigorous draw-down conditions, and, from the point of view of stability analysis, rapid draw-down was likely to be critical, and so it was decided to install pore-pressure points to enable observations to be taken both during construction and after the reservoir had been put in service.

The Building Research Station had been able to help in supplying details of suitable apparatus for the purpose and details of techniques, and in return the Author had provided them with copies of the results of his observations. They were particularly glad to have those results because very little data was available, particularly factual data, about draw-down pore pressures. So far as he knew, only a little work had been carried out and that was by the Bureau of Reclamation in the United States.

The pore-pressure measurements taken by the Author had been quite interesting. They had fluctuated with the reservoir level but with a lag depending on the position of the point relative to the distance from the free surface. Dr Cooling gathered, and hoped, that there would be more opportunities for taking further observations of the draw-down conditions. It was particularly important to assess how much of the time-lag was due to the equipment which was being used. He hoped that such measurements would be made and that particular care would be taken to see that the pore-pressure points were de-aired so that they were as incompressible as possible.

Already a brief analysis had indicated that the safe working rule given by Bishop in a Paper in Géotechnique[10] (i.e., taking the pore-pressure coefficient $B = 1$) fitted the case fairly well. Dr Cooling hoped that in due course the Author would prepare a Paper, perhaps for Géotechnique, in which his valuable observations, together with soil tests and analysis, would be put on record.

Mr W. E. Blackmore (Senior Assistant, Sir William Halcrow and Partners, Consulting Engineers) referred to the design for the major stream intake shown in Fig. 21. He assumed that the pond formed upstream of the structure would ultimately fill with gravel and that it would be necessary for it to be mechanically or manually scoured.

His firm had also been developing an intake designed to reject the flow in spates when it carried gravel, so that the conduit would take only comparatively clean water. They had, however, sought to go a little further than the Author's design and to eliminate altogether the need for any human intervention to clear the accumulated gravel at the intake. It was done by a type of intake called a scoop intake, shown diagrammatically in Fig. 24. The principle was that at low flows the water entered the intake and met an accumulated body of water in the "bowl" part of the intake. That body stopped the flow from going further and diverted it into the conduit over intake weirs on each side and past baffles which stopped floating debris. As the flow increased, it reached a stage where it had sufficient energy to sweep away the body of water in the "bowl"; thereafter it traversed the whole intake as a shooting flow which discharged over the outlet lip and escape weirs and missed the intake weirs; during that stage, therefore, no water entered the conduit. At the same time it swept away any gravel which might have accumulated in the "bowl" or floating debris stopped by the baffle during the period when the flow was

10. A. W. Bishop, "The use of pore-pressure coefficients in practice." Géotechnique, vol. 4, p. 148 (Dec. 1954).

y small. When the flow again decreased, a point was reached when it no longer had ugh energy to maintain the shooting flow and the conditions reverted to the original te; the "bowl" filled and the water passed over the intake weirs again.

There was scope for hydraulic refinements, mainly directed at narrowing the gap between value of the flow which started the shooting flow and its value when it ceased to shoot. e of the refinements was to raise the outlet lip of the structure a little above the level he side escape weirs with the effect that the increasing shooting flow, when it started to sh the body of water out of the "bowl", more or less swept it sideways over the escape rs until it established shooting flow over the outlet lip. Another refinement was htly to dish the outlet leg of the intake so as to concentrate the flow into a jet which ld almost wedge its way through the body of water instead of having to push it out ntally.

An intake of that type, constructed about a year previously, had worked very well ough it did not have the hydraulic refinements first mentioned. There was no sign of gravel having entered the conduit and there had been no need for any human attention scour out the "bowl" of the intake.

Mr **P. L. Critchell** (Technical Service Advisory Officer, Expandite Ltd) referred to methods used for sealing joints. He appreciated that bitumen plugs such as those cribed in the Paper were frequently used. There were, however, certain incom- ibles. For example, to fill a small-diameter cavity completely with a sealing material ich was poured hot, it was necessary for the material to be very fluid indeed to penetrate l fill the cavity satisfactorily. If, however, the material was of such low viscosity at t pouring temperature it was highly probable that subsequently, owing to normal nospheric conditions, it would tend to flow through the small crack which would inevit- y develop upon the shrinkage of the adjacent sections of concrete. As already icated, therefore, another material such as copper strip was necessary to retain the rmoplastic material in position.

The incorporation of 5-ft-wide shrinkage gaps, as already pointed out, doubled the mber of points where cracks might develop, and therefore doubled the number of joints uired.

Referring to the remedial treatment described by Mr Guthrie Brown, Mr Critchell stated t once the adhesion of a bituminous material had been broken by water, no amount of t would enable that material to adhere to wet concrete.

The work of the Bureau of Reclamation had already been mentioned and the Bureau l in fact developed flexible water-stops made of rubber, which were capable of accom- dating movement and so would obviate the necessity of using 5-ft wide closing sections.

The rubber water-stops developed for the reclamation work in America had been in vice since 1935, which, it was agreed, was still not a long period considering their plication to dams. They had, however, accommodated during that period movements up to 5½ in. in shear and it would appear, therefore, that joints could be spaced at quite le intervals, larger amounts of movement being accommodated by the water-stops hout fracture. The water-stops did not reply on adhesion to the concrete, but on vement which could be predicted, i.e., movement due to shrinkage. They were shaped a dumb-bell cross-section so that if shrinkage of one or other unit occurred, the flexible ber at the end bulb of the dumb-bell was tightened against the concrete, giving a ball- ve effect.

It might be argued that in the case of copper large widths of diaphragm could be used, ich would enable dense waterproof concrete to be obtained over a large area of the water- p. It had been shown, however, that shorter widths could be used satisfactorily if sonable care was taken in compacting the concrete.

Had the Author considered the incorporation of water-stops which would accommodate vement and did not rely on a bituminous sealing material, which, as Mr Critchell had icated, if satisfactory in one respect would necessarily be unsatisfactory in another?

‸ **Mr P. O. Wolf** (Lecturer in Fluid Mechanics and Hydraulic Engineering, Depart ment of Civil Engineering, Imperial College) observed that during several visits to Gle Shira in the past 6 years he had been greatly impressed by the ingenuity displayed by th Author in dealing with difficulties which, with the application of conventional method would have found less economical and aesthetically less satisfactory solutions.

The reference to his former chief, the late Mr James Williamson, was greatly appreciated for Mr Williamson had taken a keen interest in the development of the Shira catchment which in its comprehensiveness resembled that of Mr Williamson's own Loch Sloy area Mr Wolf felt that the choice of a round-head buttress of slenderer proportions, for the mai Shira dam, would not have been made by Mr Williamson, who had favoured the slightl less economical but sturdier massive-buttress type, in the construction of which less skille concreters could be employed. However, once the choice had been made, the detailed design would doubtless have received Mr Williamson's approval. That applied parti cularly to the 5-ft closing wedge between buttress heads: their advantage had bee repeatedly stressed in Mr Williamson's publications, and Mr Wolf had found at anothe large dam in Scotland that the time interval specified for the construction of adjacen blocks (cast without a closing gap) imposed on the contractors difficulties and expense i the provision of extra shuttering and the limitations on the use of cranes, which woul express themselves in somewhat higher unit rates. From the point of view of design, th advantage of the closing gap was that each buttress head could be allowed to shrin fully before the wedge in the gap was cast. If that closure took place after a period o cold weather, the vertical joints on each side of the wedge were not likely to open, eithe owing to temperature effects or because of the shrinkage of the narrow wedge. Tha applied particularly if it was accepted that the filling of the reservoir would, by the satura tion of the buttress head, cause the concrete of the upstream face to expand.

With regard to the choice of sealing strip for the vertical construction and contractio joints, Mr Wolf appreciated that copper sheet suitably shaped had much to commend it but site experience of the difficulties of bronze welding or brazing successive lengths o rigid sealing strip in the prevailing high winds led him to favour continuous strips of specia rubber or "plastic" material, unrolled as construction proceeded, and combined with bitumen which would just remain plastic at ordinary temperatures.

Mr Oscar Elsden (Senior Engineer, Sir Alexander Gibb and Partners, Consultin Engineers) was interested in the adoption, for the embankment dam, of a thin reinforce concrete diaphragm hinged at the base. It was a possible disadvantage of a wall of tha type that the leakage path through horizontal and vertical construction joints was ver short. The Author had referred to the careful preparation of the construction joints What precautions had been taken; had water-stops been introduced in addition to th customary scabbling?

Mr Elsden noted that a considerable portion of the sand used for the concrete consiste of rock crushings. That practice could give rise to a great deal of trouble owing to th presence of rock-flour in excessive quantities. For that reason some engineers would no permit the use of crushed sand in water-retaining structures. Presumably the results a Glen Shira had been satisfactory, and it would be interesting to know what measures ha been taken to wash the sand and to remove excessive quantities of flour.

Mr J. H. Thornton (Resident Engineer, Upper Moriston Works) said that to obtai fairly uniform pressure distribution under the base of a concrete dam an inclined buttres was the obvious choice. Present-day shortage of materials, however, led one to wonde if a rockfill dam might be better. He noticed that at the full height of the dam a rockfi structure was more expensive than a buttress type. What type of rockfill dam had bee examined?

‸ This and the following contributions were submitted in writing after the closu of the oral discussion.—SEC.

When comparing with a conventional mass-concrete gravity dam had the Author cluded for forming the 6-ft-wide contraction slots similar to those adopted in the lower m? They doubled the quantity of contraction-joint shuttering and Mr Thornton ubted if the benefits merited the additional expense.

The maximum output of the concrete plant had been less than one-third of the rated tput, and Mr Thornton asked if the limitation had been imposed by the rate of placing e shuttering or by the cableways. As the higher portions of the dam were being con- eted had no limitation been imposed by being able to use only one cableway; or had the bleways been placed in such a manner as to reduce that limitation?

The area adopted for the bearing tests appeared small and could not give information out the deeper-lying strata. Had measurements been obtained of the deformation of e foundations under the load of the dam structure, and if so did it differ at any place om the value indicated by the tests?

Would not a rockfill structure have been more suitable for the lower dam in view of the gh rainfall? It would have avoided the delays which occurred when placing soft aterial. In general, an earthfill dam should not be constructed in areas of high rainfall less there were also long dry periods. It was not clear from the Paper whether the rate draw-down had been limited to 5-ft/day because of the possibility of pore pressure coming too high, or if that was the maximum rate of draw-down so far experienced.

From the drawings it appeared that the station itself would be more expensive than one ilt at ground level, since the walls and reinforced concrete roof were fairly substantial. offset that, the cost of the tail-race and access tunnels had to be less than the reduction hieved in the cost of the pressure tunnel. It seemed, therefore, that for "tail" develop- ent stations generally the maximum economy was achieved by adopting the shortest ssible pressure tunnel. The limit was probably reached when the free-flow conditions uld not always be maintained in the tail-race tunnel and surge systems had to be used th upstream and downstream of the station. A short pressure tunnel could result in bstantial saving in quantity of steel, weight of alternator, and the need for turbine relief lves.

Mr Thornton noted that the shaft at Shira was dry and self-supporting and that the eight of rock overburden was sufficient to balance the water pressure. In the design of ch a shaft there would always be some doubt as to the point at which steel linings should adopted. Steel linings had some disadvantages—they were expensive, steel was not ways easy to obtain, the steel deteriorated in spite of protective coatings, and there was ways the problem of external water. They were, however, watertight and should erefore be used where the surrounding rock would deteriorate if wetted. A concrete ing on the other hand was cheaper. It decayed no faster than the rest of the tunnel d it could withstand external hydraulic load. The rock and concrete could both with- and the external hydraulic load, otherwise no allowance could be made for it in the design the composite shaft; there seemed to be little reason to use steel provided that:

(1) extremely high heads were not being dealt with;
(2) the rock cover was adequate;
(3) the station was more than about 100 ft away.

With careful grouting some degree of precompression could be applied to a concrete ing to help negate the hydraulic tension and so reduce cracking.

Could the Author give the difference in overall cost and time to form flanged and welded nts? Mr Thornton believed that the advantage lay with the welded joint which could individually tested and photographed with gamma-rays on site. Welding had been ed in modern high-head sections on the Continent and in Canada but there was a limit the plate thickness which could be jointed. Although flanges help to stiffen the pipe ainst buckling they would impede the proper placing of concrete around the pipe.

It was not clear from the Paper whether the grout holes perforated only the steel or if ey penetrated to rock. If the latter, then some of the grout would be expected to fissures in the rock. The clearances found between the steel pipe and the concrete

filling appeared to be too small to be grouted; what had been done about it? Recently Mr Thornton had found similar clearances between the steel of the top casing of a draft-tube liner and the surrounding concrete. Two holes had been drilled within the same hollow-sounding area and it was only after maintaining water pressure on one hole for some hours that signs of dampness had appeared at the other. That seemed to indicate that any attempt to inject grout would be futile, so the holes had been plugged. At the time, Mr Thornton had considered the heat of hydration to be the cause of the trouble and he had noticed that hollow areas appeared at points where small lugs had been welded to the draft-tube liner, indicating some distortion.

The Author, in reply, expressed his gratitude for the reception given to the Paper and his personal thanks to Mr Fulton and others for their kind remarks. As Mr Fulton had indicated, the development and execution of the scheme involved a wide variety of problems and it had been a very real pleasure to be engaged on such a job. Mr Fulton's observations were of special interest since he had been closely associated with the impressive development and construction of the large-scale works undertaken by the North of Scotland Hydro-Electric Board and was thus in a position to draw some very useful comparisons and weigh up the merits of the designs submitted for projected works.

The Author expressed his thanks to Mr Banks for bringing out further points of interest relating to the choice of the reinforced concrete core wall for the earth embankment of the lower dam and for directing attention to the low intensity of grouting applicable to the schists and phyllites occurring at the sites of the Shira dams.

Mr Guthrie Brown had referred to the site of the Errochty dam and compared the foundation conditions at Errochty and Shira. The Author had had the opportunity of examining the foundation rock and conditions at both sites and did not consider there was much to choose between them. It should not be concluded that the Shira foundation rock was more favourable because it absorbed a much smaller quantity of cement in grouting. In the Author's experience the quantity of grout absorbed was not a reliable criterion since large quantities of cement were frequently required when forming a grout curtain in massive igneous rocks such as sound granite, the joints in those masses being generally well defined, whereas in the soft phyllites and mica schists the rock strata comprised a series of thin pliable laminae which the grout did not readily penetrate. If one were making a catalogue of the unfavourable features of the foundation conditions at the Shira main dam, there was the soft phyllite dipping in a downstream direction interspersed with narrow intrusions of harder rock, a region of pot-holed limestone, and a badly faulted zone which crossed the site near the spillway. The figure of 10 tons/sq. ft quoted by Mr Guthrie Brown for the Shira main dam referred to the maximum principal stress in the foundation rock. The maximum vertical pressure on the foundation rock was $6\frac{3}{4}$ tons/sq. ft, which was considered to be a safe figure for the conditions.

Considering that both dams were of about the same height and had to be designed for unfavourable rock conditions which were understood to be somewhat similar, it was not surprising that the two firms of consultants appointed by the Board, working quite independently, had arrived at designs of the same general form. The detailed design of the Shira dam had been undertaken in 1947 and tenders for the whole of the civil engineering works of the project had been invited in February 1948. The tender documents for the Errochty works were issued several months later and, as explained by Mr Guthrie Brown, the construction of the Errochty dam had been carried out ahead of the Shira main dam, the reason being that the former structure was situated alongside a public highway, whereas the works access road constructed to reach the site of the Shira dam extended to a length of 9 miles.

Mr Guthrie Brown had sought to compare the relative merits of the diamond-headed form, as at Errochty, with the round-head type adopted at Shira. The Author was of opinion that there was no case for departing from the round-head form, which was the basic structural conception, unless it could be established that the substitution of a series of straight faces, as in the diamond-head buttress, was more economical. The curved

ttering for the upstream face of the Shira round-heads had not been in any way plicated and the panels had been raised stage by stage without difficulty (see Figs 6 7). There had been no awkward mitres to form as in the diamond-headed type and lysis of the actual prices quoted had disclosed that the unit rate for the curved shutter- was about 67% of the unit rate for the straight shutters at the sides of the buttresses, re mitres had to be formed. Having seen the shuttering schemes for both dams ch, as explained by Mr Guthrie Brown, were being built by the same firm of contractors, Author was satisfied that the round-head design was the more suitable for the con- ons at Shira and would not hesitate to repeat it under similar circumstances.

he inspection shafts referred to in the Paper had been of considerable assistance ng the construction stage and served as a permanent means of access to the foundation ns. The provision of the shafts had not added to the cost of the dam since the cost he shuttering had been offset by a saving of concrete.

r Guthrie Brown had criticized the block and gap construction adopted at Shira and compared it with the alternate block method adopted at Errochty, stating that the er procedure provided greater structural isolation of the individual buttresses. Block gap construction had been adopted for a number of dams as a means of reducing ndary stress effects and joint contraction caused by shrinkage. As stated in the er, the Shira design had been developed with due regard to the variable nature of foundation rock to provide the maximum possible degree of structural isolation. ough the number of joints was thereby doubled, the main problem to be dealt with he design of the joints, namely shrinkage, could be largely dismissed when the block gap method was adopted. Having observed the manner in which the contractor had n able to raise the buttresses in groups, thus minimizing the handling of shutters n one block to another, the Author was satisfied that the block and gap method offered erial advantages which were reflected in the unit rates quoted for the work, and he of opinion that those advantages more than outweighed the disadvantages to which Guthrie Brown had alluded.

r Wolf, who supported the Author's contentions relating to the advantage of block gap construction, had rightly directed attention to the difficulties which arose on se exposed sites when using copper sealing strips. The erection and maintenance of se sealing strips admittedly required very thorough supervision on the part of the ection staff and in that respect the rubber or plastic type of sealing strip was preferable.

r Critchell had also commented on the relative merits of rubber water-stops and per bitumen for sealing the joints of a dam. Rubber water-stops had not been in eral use in Britain when the Shira works were issued to tender. Soon after they were oduced commercially the Author had a series of tests put in hand in an endeavour to ain reliable data regarding the probable life of rubber seals subjected to those working litions. The tests had necessarily taken some time to carry out in an attempt to ulate long-term conditions and in the interval a final decision had to be taken regarding joints of the Shira dam, the use of copper-bitumen seals being confirmed. On com- ion of the tests referred to, the Author had been satisfied that rubber water-stops an application to such works and offered advantages in certain respects. He had pted them for another dam which was at an advanced stage of construction. One dvantage he had encountered in the use of rubber water-stops had been that of uring thorough compaction of the concrete against the rubber. The plastic material rred to by Mr Wolf was rather better in that respect and he was of opinion that there scope for the production of heavier sections of that material for structures such as s, the sections commonly produced being suitable for use in tanks and other such l-retaining structures.

he problems to which Mr Critchell had alluded relating to the use of bitumen seals llustrated for the Shira dam had not arisen because means had been adopted to obviate e difficulties. The bitumen used was not of a very fluid type, as suggested by Mr chell, but was of a stiff consistency. When the work at each section of the dam was ciently advanced to enable the filling of the 5-ft-wide gaps to commence the open

sides of the diamond-shaped recesses were shuttered to form a container for the bitume and hot liquid bitumen was filled in to a height of approximately 5 ft around a long tubula shaped immersion heater centred within the recess. On stripping the shutters supportin the outer faces of the column of bitumen the concrete of the closing gap was raised on lift and when that was set the immersion heaters were switched on. Those heaters wer of a rating sufficient to remelt the bitumen which penetrated into the pores of the recentl formed abutting faces of concrete. The heaters were then withdrawn by a carefull developed technique to eliminate blow-holes or cavities and were then positioned read for proceeding with the next lift. Before adopting those arrangements full-scale test had been carried out with precast concrete blocks, so arranged that the joint faces coul be separated for examination. When the immersion heaters were omitted there had bee occasional evidence of blow-hole formation but the tests incorporating the heaters ha given very satisfactory results, confirming that the methods developed should provide a efficient seal.

Contrary to Mr Critchell's suggestion, the upstream copper strip provided at the Shir dam had not been introduced to retain the bitumen in position but was the first barrie against leakage with the bitumen forming a second independent seal downstream of th copper.

Provision had been made for measuring deflexions during the filling of the reservoi and for recording the relative movement between adjacent sections of the dam at th closing gaps. It was agreed that the bearing areas of the rock loading tests referred t in the Paper were of very limited extent and efforts were being made to correlate the result obtained with measurement of the deformation of the foundation rock under the loading o the dam structure.

The Author was indebted to Mr Blackstone for contributing further information on th mechanical plant with particular reference to the Sron Mor generating and pumping se of which brief particulars had been included in the Paper.

Dr Jaeger had rightly emphasized the value of model investigation on works of tha type and the Author was grateful for the assistance he had received from Dr Jaeger an others who had undertaken those investigations, since the results had been most helpfu in finalizing the design of certain sections of the work. The expenditure incurred on th model experiments had been saved many times over in economies achieved in the design

From the design point of view the most complex problems to be resolved had been thos relating to the effect of sudden drawdown on the stability of the earth embankment o the lower dam. That was a relatively small structure, but analysis by the several theorie propounded had confirmed that investigation by means of pore-pressure measuremen would be necessary to assess the order of the stability factor for a given rate of drawdow Dr Cooling had expressed the hope that there would be further opportunities of recordin the pore pressures under drawdown conditions and the Author was confident that wit Mr Fulton's helpful co-operation further data would be obtained as operating condition permitted. On obtaining a comprehensive series of records it was intended to subm the details for publication.

Mr Thornton had enquired if a rock-fill structure would not have been more suitab for that section of the lower dam. Rock-fill construction would have been more co venient but also more expensive since the filling would all have had to be quarried. Th earth embankment was a relatively small element of a large scheme and, although the had been delays in its construction, to which reference had been made in the Paper, tho had not affected the overall completion of the project and commissioning of the ma generating plant. The drawdown of 5 ft per day was the maximum rate so far experience and the records of pore pressure obtained to date indicated that for the range investigat the dam was well within the desired factor of safety.

Mr Blackmore, in referring to the design of the major stream intakes, had pointed o that the pool formed upstream of the structure would tend to fill with gravel. As explain in the Paper, the designs had been developed with due regard to the tendency for deb to accumulate at any barriers formed across those watercourses and the intakes shou

function in a satisfactory manner even if the gravel accumulation built up to spillway l.

Ir Blackmore's suggestion for a self-cleansing type of intake appeared to suffer from disadvantage that the flow to the aqueduct was cut off entirely during flood periods. a high-head scheme such as Shira that would represent a considerable loss of revenue e short intermittent spates were a frequent occurrence, being a significant element he annual run-off. The Author's firm had also developed a type of intake arranged deal with the trash passing downstream during spates. The design had not been sidered suitable for general application to the Shira scheme and the Author had not uded a reference to it in the Paper. In place of the usual weir a concrete sill was med at the downstream end of a natural pool in the stream and the water was diverted chamber at the side of the pool constructed with the necessary trash baffles and self-ulating inlet well as for the large stream intakes shown in Fig. 21. The proportions he pool and sill were so arranged that any debris which might accumulate would not rict the entry to the aqueduct and would be swept downstream during flood periods.

Ir Elsden had enquired regarding the joints of the reinforced concrete core of the th embankment for the lower dam. Copper sealing strips had been provided in the tical joints and the horizontal joints had been thoroughly scabbled and bonded with yer of stiff grout. The application of bituminous emulsion to the outer surfaces of the l, as referred to in the Paper, had been provided essentially as a protection against erioration of the concrete and consequently of the reinforcement, since the wall was ried and inaccessible for inspection or maintenance. The emulsion coatings also ved as a useful means of sealing any deficiencies there might be in the joints of the core. The rock sand used in the concrete was all washed to remove fine dust and rock flour l complied with B.S. grading. The site quarry plant incorporated "Sandor" equipment l was operated to produce the maximum quantity of sand obtainable by economic rking. Tests carried out proved that a high proportion of the rock sand could be used he mix without detriment to the workability of the concrete, and for a given cement tent and water/cement ratio an increase in the proportion of the rock sand raised compressive strength.

Ir Thornton had commented on the choice of an inclined buttress type for the main n and had suggested that there might have been some advantage by adopting rock-fill struction. The alternative design prepared for rock fill had been in accordance with mal practice and incorporated a flexible reinforced concrete membrane on the up-eam face. Any deviation in matters of detail would not have altered significantly the t relation given in the Paper, since the rock fill would have had to be quarried in any ent and there were deep deposits of peat on the site which would have had to be excavated d backfilled with rock fill. In Britain the relative prices of concrete and rock fill were h that rock-fill construction was seldom more economic unless a considerable proportion the material was available from excavations necessary for other works. The position s reversed in many parts of the world where skilled labour was in short supply. In ne cases owing to climatic conditions rock fill was favoured because the work could oceed over a longer construction season.

The Author had been associated with another Scottish hydro-electric scheme for which ntractors tendering had been invited to quote alternative prices for concrete gravity d rock-fill construction. The dam referred to had a maximum height of about 75 ft d the site conditions were favourable for rock-fill construction but the tenders for that sign had been fully 33⅓% higher than those submitted for concrete gravity construction. e concrete design was generally similar in form to that adopted for the spillway section the Shira lower dam including 6-ft-wide construction gaps. The Author had given views on the relative merits of block and gap construction in his reply to Mr Guthrie own's contribution.

The rated output of 100 cu. yd/hour given for the main batching plant compared with maximum of 70 cu. yd/hour for the capacity of the cableways. The batching plant s used for supplying all other concrete works in the vicinity of the main dam and the

margin was provided to cover the peak requirements having regard to those other works. In comparing the weekly output with the hourly ratings of the mixing and concrete-handling plant, allowance had to be made for weather conditions and the effects of working 12-hour shifts including night working, also the progress with the erection of shutters and other operations for which the cableways were used on occasion. The cableways had been arranged so that both machines could be used when concreting was proceeding at the higher portions of the dam, but there was a moderate reduction in the load carried since the cables had to be tensioned to provide the requisite clearance when passing loaded skips over the partially completed sections of the dam.

As stated in the Paper, the decision to provide an underground station at Clachan had been taken following comparison of the tender prices for alternative surface and underground layouts. Mr Thornton had suggested that the walls of the underground station were fairly substantial. Those walls comprised panels of common brickwork, 14 in. thick, and the cost had been very much less than would have been required for a surface station since the latter would have been faced with masonry to conform with amenity requirements. In that case, the adoption of a "tail" development with a short pressure tunnel had been ruled out since it was desired to divert the tributary streams along the route of the main tunnel into the pressure system.

As Mr Thornton had stated, there was always some doubt regarding the point at which steel linings could be dispensed with in pressure tunnels and shafts. The rock conditions at Shira were such that steel lining had been considered essential for the greater part of the length and a change to concrete lining, involving the provision of special shutters for the upper section of the sloping shaft, had not been favoured. Whilst efforts had been made on some schemes to pre-compress concrete linings by grouting, the results were likely to be doubtful when dealing with rock which varied in quality from point to point. The grout holes at the Shira pressure shaft had extended through the steel and concrete lining to the rock, and the main purpose of the grouting had been to ensure that there would be no open fissures or cavities around the encasing concrete. An effort had been made to inject grout into the clearances around the steel lining and that had confirmed that the clearances were of a very minor order which would close up on filling the shaft by elastic deformation of the steel lining. The flanged joints had not impeded the placing of concrete around the pipes as had been suggested by Mr Thornton. The steep slope of the shaft had been helpful when placing the surrounding concrete and immersion vibrators had been used with good effect.

Welding might have been adopted more extensively, but as indicated in the Paper the Author had not been satisfied that dependence should be put on overhead welding for the high pressures involved. The position was different where the welded joints had been introduced since the welder's position relative to the weld was much improved on the slope. For the thicker plates site welding had been considered impracticable and for the thinner plates the welded joints had been less expensive. The flanges had been manufactured in pairs and matched at the pipemaker's works. There had been no difficulty in bringing them together at the site and the flanged joints had generally taken no longer to make than the welded joints. Had the welding been extended to thicker plates the time for making those joints would have been greater than for the flanged joints.

Mr Thornton had listed certain criteria relating to the conditions under which steel lining could be dispensed with. The Author did not favour the general acceptance of such broad assumptions and considered that each case should be examined with due regard to the circumstances, particularly the nature and condition of the surrounding rock. In designing a pressure shaft or pipeline for works of that magnitude and head the designer must have particular regard to the risks involved and the serious consequences which would arise should a failure occur on such an important element of a scheme; a form of conduit which might be appropriate on a small-scale low-pressure installation would be unsuitable for works of much greater head and scale.

JOINT MEETING

THE INSTITUTION OF CIVIL ENGINEERS
THE INSTITUTION OF MECHANICAL ENGINEERS
THE INSTITUTION OF ELECTRICAL ENGINEERS

at the Institution of Mechanical Engineers

27 April, 1956

THOMAS ARKLE CROWE, M.Sc., President, I.Mech.E., in the Chair

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The Second Graham Clark Lecture

THE IMPACT OF ENGINEERING ON SOCIETY

by

*** Sir Maurice Bowra, F.B.A., M.A.**

-OUGH I am much honoured and flattered by your invitation to speak to you this -ning, I cannot conceal that I have no qualifications to do so. I am, I fear, a -ng fossil, a specimen of unmechanized and even of pre-mechanized man, in my -n way as outdated as the coelacanth or the metasequoia. I cannot drive a car. -ypewrite with two fingers. I am singularly maladroit when it comes to mending most humble things. But perhaps it may be instructive for you to know that -h people exist, for whom your own resplendent universe of intellectual endeavour -. closed mystery, an enchanted domain which they indeed admire from outside . whose secrets they can never hope to share. I hope you will not think me -pertinent if I claim that even so ignorant a view as mine may perhaps serve some -pose. It is often profitable to see ourselves as others see us, especially if we -ctise some highly skilled and specialized pursuit. However ill-informed the -ws of an ignorant stranger may be, there is always a hope that they may give us -ew angle or turn our minds to something which we have neglected. I have often -hed that we possessed, for instance, the record of what the first American Indians -ught who were brought to the court of Queen Elizabeth I. It would indeed be -ange. Much of it would be quite wrong and even absurd, but somewhere in it -re might be a new ray of light of which no Englishman would have thought and -ich would yet illuminate that remarkable world. I would ask you to look upon as just such an aboriginal, snatched from his own world and fascinated by the -steries of yours. My own studies are concerned with the study of man, even if -y approach him from a rather special and specialized angle, and no student of man afford to be unaware of what engineering means in history. I will therefore do best to speak from my own standpoint and hope that it will not seem to you to too misinformed, too reckless, or too infantile.

-Man, says Beaumarchais, differs from the beasts only in drinking without being

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* Warden of Wadham College, Oxford.

thirsty and in making love all the year round. However important these differences may be, and please do not think that I underestimate them, I would claim that man differs from the beasts mainly in being able to turn nature to his own use. Of course some animals can do this, but only on a very small scale. The pride of man is that he has already done so on a large scale, and seems likely to do so on a still larger one. By the construction of inanimate objects, which we call machines, we have extended on an incalculable scale what we are able to do. The process began a very long time ago, but it has on the whole been slow until quite recently, and it has by no means been regular. At the very start are the unknown inventors, who made discoveries which indeed showed what the control of natural forces may mean. If, as is possible, Peking man, *Pithecanthropus Pekinensis*, really knew how to make fire, it is possible that he should be regarded as our forerunner, since without his discovery nothing would have happened. If he was closer in his structure to the apes than to *homo sapiens*, our debt to the beasts is greater than we usually admit and there is much to be said after all for having our ancestors not in Paradise but in the Zoological Gardens. If Peking man does not quite qualify to be the patron saint of engineers, he should perhaps be remembered on their Founder's Day and have a place in their Golden Book of Benefactors.

Now almost every society of which we know anything practises engineering to some degree. Even the Australian aborigines invented the boomerang, which was an ingenious and amusing means of hitting your enemies. But it is only in the last hundred or so years that society has really become mechanized on a large scale. The difference between ourselves and the ancient Egyptians is not that we admit the existence of engineering and they did not, for after all the construction of the Pyramids was an extraordinary achievement, but that they did not see the range of its possibilities. A considerable degree of civilization can be secured with a minimum of engineering and, though we must certainly admit that without engineering civilization is impossible, it is not always of first importance. In the eighteenth century China under the great Manchu Emperors not only appealed to the philosophers of the west as a model of good government and social graces, but can be seen today to have shown a remarkable capacity for organizing an enormous area into law and order and for producing, at least in a limited class, a high degree of intelligence, sensibility and creative endeavour. The Chinese, who led the world in the invention of printing, the mariner's compass, and gunpowder, did not advance from these auspicious beginnings but evolved a civilization in which engineering had almost no place. Even their buildings, graceful and charming though they are, were modelled on tents and called for no great skill in their erection. It is true that the Emperors used Jesuit missionaries to make fountains and clocks, but there they stopped. So far as the external equipment of life went, China in the eighteenth century differed in no essential respect from China in the first. The Chinese, for all their intellectual gifts, failed to see how important even clocks and fountains might be to those who understood the principles on which they worked, and in due course they paid heavily for this when a mechanized Europe attacked them and imposed its will on them.

An even more notable example of this neglect can be seen in the Greco-Roman world. The Greeks were in some respects pioneers of engineering, and the many buildings which still bear witness to Roman competence belong to the same tradition. There were indeed times when it looked as if the Greeks were on the verge of great mechanical discoveries. Archimedes was not only a mathematician of incomparable genius but at times turned it to practical uses, as when he invented hydrostatics or

vised engines of war to confound the Roman besiegers of Syracuse. Yet, despite ese promising beginnings, the Greeks stopped and did no more for engineering. or did the Romans after them. And for this, like the Chinese, they paid a heavy ice. If the Romans of the later empire had only had another Archimedes to vent new engines of war, they would have had no more difficulty in disposing of tila and Alaric than Kitchener had in disposing of the Khalifa. The trouble with society which does not believe in engineering or see its possibilities is not that it nnot be civilized, but that it is not likely to survive. Civilization is a sensitive ant, and its first duty is to look after itself.

This failure of two great systems deserves a moment's notice. We cannot but ask ny neither China nor the classical world exploited the possibilities of engineering. hatever the cause was, it cannot be ascribed to religion. Neither the system of onfucius nor the Olympian Pantheon was opposed to the mechanical sciences. deed in their early days the Greek gods were regarded as patrons at least of building d handicrafts, and Hephaestus was without doubt an engineer in the modern nse when he made mechanical beings to work for him in his arms factory. The planation must lie elsewhere, and perhaps we may find an illuminating hint in what utarch says of Archimedes and his more practical inventions:

> Though these inventions had obtained for him the renown of more than human sagacity, he yet would not deign to leave behind him any written work on such subjects but, regarding as ignoble and sordid the business of mechanics, and every sort of art which is directed to use and profit, he placed his whole ambition in those speculations the beauty and subtlety of which is untainted by any admixture of the common needs of life.

Now we might think this no more than the personal whim of a pure mathematician no preferred his own chosen field of geometry to any impure application of it. But e important fact is that this was the normal attitude both in the Greco-Roman orld and in China. The engineer was somehow thought to be sordid and engaged tasks below the dignity of a civilized man. We might, of course, say that you ust expect this to happen when education is almost entirely based on the study of erature and words have such a priority of prestige that anything else fades before em. Now this may well be true of China or imperial Rome, and I must admit with gret and shame that too exclusive a study of words may well breed illusions of andeur about their pre-eminence and blind their devotees to other matters of first portance. But this is hardly true of Archimedes. He was certainly not a pure oduct of a literary education. He had behind him some three hundred years of athematical and even of scientific thinking, which did not shrink from experiment d liked to confirm its theories by precise observation. It looks as if we must ok deeper for an explanation.

The contempt for applied mechanics displayed by Archimedes was a product of a ciety in which there was no shortage of cheap human labour. The trouble with the cient world was that it never had any difficulty in finding men to do tasks which assume should be done by machines. Some of these tasks must have involved a deous expense of effort, and whether we think of the Pyramids or Stonehenge or e Great Wall of China or the roads of the Roman Empire, in each case we must member that, though some mechanical appliances were used, most of the work as done by human hands. The existence of an inexhaustible labour-pool, of men no for the barest and meanest subsistence were able and ready to carry out tasks great physical difficulty, meant that the educated and governing classes never

turned their minds to other, and better, ways of getting such work done. Their minds, so brilliant and active in other ways, were on this point closed. Because human labour was so abundant, it never occurred to them that this was not the best way of doing what they wanted to do, still less that it could not do everything possible for men. They assumed that this was the unchanging pattern of human life and never looked beyond it. If inventions were to come, they would not be from those who alone had the power to see that they were used, and if some more far-sighted man saw their possibilities, the chances were that he would find nobody to listen to him. By a happy accident we have a treatise written by such a man at the end of the fourth century A.D. We do not know his name, but his tract *On Things of War*, which recommends some ingenious new military engines, shows the position, when he says:

> It is universally agreed that in the technical arts (among which we include the invention of weapons) progress is due not to those of highest birth or immense wealth or public office or eloquence derived from literary studies but solely to men of intellectual power (which is the mother of every excellence), depending as it does on a happy accident of nature.

The Romans, like the Chinese, rejected machines in the last resort because their ruling classes were snobs.

This is a social fact of first importance, and it is not irrelevant to modern times. The prodigious growth of engineering since the end of the eighteenth century has indeed been rendered possible by the epoch-making inventions like the internal-combustion engine, but this itself would never have happened, or at least never have been turned to general use, if there had not been a complete change towards the part played by engineers in society. The old snobbish position had been so complacent that it was not so much hostile to engineering as completely oblivious of it. What was needed was something to break this complacency and suggest that after all engineering might do good even to those who thought they needed it least. This change was mainly due to the vast revolution worked by the dramatic appearance and rapid growth of natural philosophy. Just as the first Greek scientists moved without difficulty from inquiring about the nature of Being into inquiring about the nature of Becoming, and thereby opened the door to all kinds of physical speculation, so the natural philosophers of the seventeenth century saw that it was impossible to separate the nature of things from their appearances, and conducted experiments to see how things work as they do. The revival of observation and experiment, which had been almost dead since Aristotle conducted his great researches into biology, meant that nature began to become intelligible, and when this happened, men saw that they could make use of it.

This momentous change was not made without obstacles. Even after the foundation of The Royal Society and the first brilliant outburst of scientific speculation which came with it, it looked at one time as if it would again fade away as it had centuries before. It was saved by the recognition that machines could do much that men cannot do by themselves, and though such an idea might still seem absurd or repugnant to the select and privileged few, it was welcomed by others who saw in it a hope for improving their own lives and conditions. Economic forces undoubtedly played an important part. Once they began to undermine the old social order and to create opportunities for many who had hitherto been forced to be content with a humble station, they set new challenges which soon found responses. Once it was clear that it was both profitable and honourable to know about mechanics, mechanics

gan again to produce its own men of genius, and from the time of Newton onwards e process has continued not merely without interruption but with ever-increasing rce and popularity and respect.

It is important to note that this vast change has not been revolutionary in the litical sense. It has indeed changed the whole appearance of society and done uch to change its structure, but it has not been aided by political revolution or had ery much to do with it. The leaders of the French Revolution were not the new nd small class of engineers but lawyers, doctors, lapsed priests and impoverished urnalists. The Russian Revolution made its first and by far its strongest appeal a peasantry appalled by the destruction of war and hungry for land. The Chinese evolution was the final stage of a long struggle against officials, landowners and oney-lenders. In none of these did applied science play any leading part or supply nything like a revolutionary ideology. Indeed we may suspect that if these three untries had been more mechanized than they were, revolution might not have come all or have come in a different, less virulent, form. It was because these people lt that violence was the only solution for their troubles that they took to it. Now ngineering tends to suggest always that there is a cure for most evils, and that the ge-old troubles of man such as starvation, disease, floods, and the like can be surounted by a proper use of machines. It is indeed significant that the classic case growth without revolution should be in a country which has used engineering on e greatest possible scale. The United States, which was brought to birth by revolt, as, despite the inevitable disorders of its first expansion and the catastrophe of the ivil War, never come near to social revolution and seems determined at all costs to void it. This is all the more remarkable when we consider how many immigrants the nineteenth century arrived with advanced radical opinions and how sharp e social conflict was in the period of the great millionaires after the Civil War. ere, we might think, was an ideal powder-barrel, ready to blow up at the first pplication of a match. But it has not. Though the United States owes more than ny other country to the practical application of mechanics, and has won its successes ith a good deal of strain and trouble, it has remained remarkably faithful to its ndamental assumptions of what American life ought to be.

If, as we well may, we regard politics as the struggle for power, engineering is not political activity. It aims at something quite different—the control and exploitaon of natural resources to give a greater degree of human welfare. It becomes olitical only when its very existence is threatened by authority, and that may have een common enough in the past but seems less and less likely to be common now, when it is taken up by authority for its own ends. In itself it stands outside and eyond politics, and the outlook which it represents is essentially non-political, and we wish to know what it means for society, we must not look at it entirely or even ainly from a political angle. It embodies in the first place a special outlook, which that man's struggle for existence cannot merely be maintained by exploiting atural resources but can even be made progressively less laborious as knowledge of eir control increases. This is not a Utopian dream, not another form of the old ish to regain a lost Paradise or to return to a Golden Age. It can call as witnesses its realistic good sense its own achievements and show that these have indeed done mething beyond reckoning to ameliorate the human lot and positively to improve . It is all very well to look back with regret to the age of the Antonines or of ouis XIV or even of George III, but I am very suspicious of this particular brand f intellectual opium. I would not deny that our own century has had its appalling atastrophes, but I would confidently assert that life is more agreeable now for the

mass of mankind than it has ever been, and that this is almost entirely due to man's increasing conquest of nature through machines. Agreeableness may not be everything, and not even a final test, but it is after all something, and this at least we owe to the engineers.

The engineer works within his own social frame, and as the modern world is organized into national states, his work has to be shaped to suit them and their demands. Within these limits his work is a strong stabilizing influence. On the one hand it avoids the angry discontent which is inevitable when no change seems possible, and on the other the complacency which assumes that everything is after all as good as it can be and that nothing need be done about it. Unlike the fine arts, which are always having to make a fresh start because something has been done so well that it cannot be done again, it moves in an ordered progress in which every new step is a real advance and leads to others beyond it. Such a process satisfies both man's desire for order and stability and his love of novelty. He likes to think —and who shall blame him?—that many new delights lie round the corner, but he shrinks from paying too heavy a price for them. Each new discovery has to be turned to practical use, brought into general circulation, and consolidated inside the social frame. This takes time and patience, but nobody denies that it is worth it. A society which has become accustomed to seeing its own life improved by many inventions will develop a rational approach to its problems, realize that stability is something almost beyond price and be very cautious of losing it.

This aspect of engineering is extremely relevant to the modern world. In the last forty years some eight hundred million people have passed through violent revolution which has destroyed the fabric of society in which their fathers lived. These revolutions have indeed been political in that they have transferred power from one class of people to another and have held out enormous promises of improved ways of living. Both in Russia and in China revolution has been followed by prodigious efforts to apply science to all kinds of life. Now in this there is undoubtedly an element of propaganda. When promises have been made, men will ask that they are kept, and the most sensible way of keeping revolutionary promises is to increase prosperity by engineering. Nobody will dispute the practical wisdom of Stalin or of Mao-tse-tung in telling their peoples that if they will only study the right technology, all will in the end be well and the rapturous hopes of their youth fulfilled. But this element of wordly wisdom is matched by another. The governing classes of revolutionary states may have come to power by violence, but the last thing they want is that this violence should continue and be turned against them. They see that if they can only induce a proper respect for engineering, their subjects will realize that conditions can indeed be improved and will put up with a good deal of discipline and regimentation in the hope that in the end they will be better off. They are wiser in their generation than the later Emperors of Rome or the Manchu Emperors of China, since they see that, though men can indeed feed on hopes for a long period, sooner or later these hopes must be turned into something more substantial.

If we could believe in progress with the happy optimism of the nineteenth century, we might well think that the increasing command of mechanics would inevitably lead to the greater happiness of mankind. In principle there is no reason why it should not, but our own age has issued too many warnings against vaulting hopes for us to be able to believe it. It has learnt to its cost that mechanical progress can too easily be defeated by political insanity and that just because engineers are confined to their own social and national systems, they can do little or nothing to prevent

Though our own century has made technical advances quite as great as those the nineteenth, it has not enjoyed that prolonged peace which Great Britain oyed from 1815 to 1900 or that sense of security which is based on the belief that st social problems can in the end be solved by a more generous distribution of terial goods. Both international war and class war have dominated and damaged lives despite the obvious increase in most countries of prosperity and ease. For s we must blame man in his capacity of a political animal. He has failed to lve means by which his desire for security and prosperity can be combined with er darker and less rational forces in his nature. We cannot but ask whether gineers must not to some degree bear the blame for this, whether they have not, eit unwittingly or unwillingly, sharpened these conflicts and made them more dly.

n a fair judgement, if the engineers are to blame at all, it is for sins of omission her than of commission. I would not deny that they have created weapons of truction such as our ancestors never dreamed of, but at least it can be said on their half that in this they were the agents and the servants of political power, that it s not after all their own ambition to fashion instruments which may blow up the rld. The blame for this lies with the mass of men who insist upon destroying h other. Where the engineers have gone wrong is perhaps in taking too modest iew of their own task and their own duties. They have set out, in all sincerity l decency, to improve the human lot, and they have assumed, reasonably enough he world were reasonable, that this means a greater exploitation of natural urces for the general benefit of humanity. But this, unfortunately, is not always at humanity asks for. When, for instance, we look back to 1914 and see how sperous Germany was, how rapid were her advances in all branches of applied nce, how doctors of engineering from the Technische Hochschule at Charlotten-g seemed to have before them the whole wide world from the Rhine to the Yangtse, must surely be amazed not only that the Germans insisted upon going to war but t they acted in a spirit which denied and rejected the good things which were ady theirs so abundantly. It is impossible to read the German literature of the of William II without seeing how many serious and high-minded Germans ired war as a protest against what they thought to be the enfeebling, unmanly uence of peace. Nor was this spirit confined to Germany. It was hardly less ious in England where young men like Rupert Brooke went gaily to their dooms he conviction that they were getting away from a scheme of life which stifled their t impulses and placed far too much emphasis on comfort and security. This it was indeed to perish in the blood baths of the Somme and Paschendaele, and ngry reaction set in against it. But it is never very far from the surface and has erted itself again more than once in more brutal and less romantic forms. While engineers labour to make life easier and more agreeable, the mass of men accepts r contribution for a time and then, in wild frenzies of unreason, rejects it and troys it.

or this I can see no cure. It is not easy to find an emotional equivalent to war those who like war, or at least like to send others to it. But if what is wanted is itement, if what some men resent in ordered society is that it is too dull, there can no doubt that engineering can offer them thrills in plenty. The conquest of the which we now take almost for granted, has provided not only problems to be ed at the highest intellectual level but the practical application of their solutions a confidence which is the modern equivalent of heroic courage. The conquest amine and drought by the proper control of water supplies calls for generalship

at the top and consummate discipline and skill among the other ranks. The exploitation of new sources of power calls both for strategy and for tactics in many unfamiliar corners of the globe and evokes visions of advances over enormous fronts. Engineering, more perhaps than any other branch of human activity, provides an imaginative equivalent to war, and has the advantage that it creates instead of destroying. Whether mankind will learn this in time is perhaps too much to ask. But let us at least indulge in a faint and pious hope that it will.

If it is true that some men find a well organized and well mechanized life so dull that their only release is violence, we can at least say that it is their own fault and that they have only themselves to blame. For to be bored to this degree is surely a terrible failure in oneself. But there are more subtle and more specious criticisms than this against the growing part which engineering plays in the world, and especially against the almost incredible increase of speed in communications which we have seen in our own lifetime. When I was a boy I rightly thought it wonderfully exciting to travel from London to Peking by Siberia in a fortnight; how different from the six or more weeks by sea. But now a fortnight seems far too long for a journey to anywhere except to the moon. To the man for whom travel is a means to something else this increase of speed is of course a blessing. He wastes far less of his time than before in getting from one place to another. Air travel may be dull, but it is not so dull as a long journey by sea or so dirty as a long journey by train. In the short time at our disposal in this life it may be comforting to know that we waste less of it than we used to on the mere means of our professions and have more time to devote to their ends. Yet we may perhaps wonder whether this change in the whole character of communications has not been bought at rather too heavy a price.

Nobody who is interested in human beings can fail to take pleasure in their enchanting variety, not merely in their individual differences but in their differences of customs and thought and circumstances. The great humanistic tradition which has dominated our thought for some four hundred years accepts the variety of men as something delightful and desirable in itself and judges the worth of a civilization by its ability to sustain the widest variety possible. When we think of the rich range of existence which was taken for granted in Italy in the fifteenth century, or in France in the nineteenth, we cannot but feel respect for the ideal which holds that freedom expresses itself in variety, and that variety is a test of the richness of life. Conversely, to conform to a standard pattern seems to be an admission of defeat, of an inability to get beyond mere existence to a good existence, of a lack of enterprise and ultimately of a real self. Anyone who likes the human species and enjoys its capacity to express itself in different ways must surely be a little alarmed by the formidable drive towards conformity in our time. It is, of course, partly a political matter. The governing class of Russia spares no pains to turn its curiously assorted victims into a respectable imitation of the old bourgeoisie, and its motives are clear enough. It feels that once such respectability is established and becomes common form, the whole business of government will be easier and safer. In the United States the desire for conformity is no less powerful but comes not from above but from below, from a real desire to have a common American way of life, in which everyone feels at home and knows that he will not be troubled by anomalies and eccentricities. But though the drive towards uniformity is undeniably political in its origins, it has no less undeniably found a powerful ally in engineering.

The revolution of communications has meant a vast change in traditional ways of life by the introduction of standard international objects of every kind. The process which began with the bicycle and the sewing-machine has extended to most mechan

devices and no doubt Bokhara is as proud of its up-to-date materials as Peking. t on the whole this air of "Westernization" is probably more superficial than we nk. Of course there is an international level of comfort which spreads along main lines of communications and supplies the same meals, the same drinks and same opportunities for hygiene wherever it occurs, but this after all is meant for eigners and does not touch the local inhabitants. They will maintain their own *sine bourgeoise* and reject all temptations to be "Ritzy" in their *confort moderne*. deed the spread of Western gadgets to Asia may even have its own charm. It is modern equivalent of the Baroque churches which the Portuguese built at Goa d Macao, or those resplendent palaces which the English built in the best Regency le at Hyderabad or Corfu. We cannot expect any material civilization to remain tic, and the archaeologists of the future will probably be as delighted to find mains of gramophones and wireless sets in Ulan-Bator as their present counterparts to find Roman coins and pottery in Travancore.

Nor need we deplore the way in which most languages now absorb with consum- te ease words from other countries. The French have long set a mysterious ample with their use of "un footing" or "un dancing", but there are few languages ich do not yield to the same temptation. For a time the Chinese resisted the option of foreign words and preferred to call whisky "fire-water", but I am told t this is now out of fashion and whisky is simply whisky, just as the Bulgarian for ackintosh" is "mackintosh". The Russians, who began by calling a railway minus "voksal", which comes from Vauxhall, have from time to time resisted eign words but now, like the Chinese, have given up the struggle. Even modern eek, torn as it is by dissension between using a stiff Byzantine "pure" language d the lively varied speech of the common people, cannot resist such modernities as *ανεξ* and *αιλαιφ*. Most languages have a remarkable gift for absorbing words m abroad. The process is probably as ancient as civilization, and the first Greeks re delighted to take over such pre-Greek words as those for such non-Greek things bath-tubs, beans, hyacinths, and wicker-baskets. When the Germans insist on ling the telephone "Fernsprecher", they show an unbecoming nationalism, and ignorance of the laws of that philology to which they have given such patient and tiring toil. These linguistic oddities have of course increased with the increase of mmunications, but they do not in fact detract from the charm of the languages ich assimilate them.

A more serious charge against the influence of engineering is that it interferes with variety of the individual self and shapes it to a uniform mould by imposing tain patterns on it through modern organs of indoctrination such as the press, ema, wireless and television. It is claimed that these means of instruction and opaganda are far more tyrannical than the old-fashioned means of books because ey are cut to a close pattern and allow very little choice. It is perhaps not enough say that we need not listen to them unless we wish; for sometimes we may be in mood to listen to anything, and then, it seems, the deadly work begins. Now of urse if we compare the means of information which the ordinary man of today has comparison with the privileged man of a hundred years ago, there is no doubt that s more stereotyped and far more likely to create what is disagreeably called a mass nd. The danger is indeed great when these means of information are controlled a single authority which wishes only certain things to be known, and those not cessarily true. We have seen this happen in Germany and Russia, and we know w dangerous it can be when even the most honest and independent people are so cumscribed in their sources of information, and so cut off from any other sources,

that they are almost forced into certain opinions. Hardly less dangerous is the situation in relatively free countries when an exaggerated respect for the views of misguided but touchy minorities forbids the public expression of anything which might cause them pain. Truth flourishes on controversy, and when the B.B.C. seeks to avoid it or to reduce opposite points of view to a woolly muddle, it betrays its heritage and shirks its chief duty.

Against this somewhat depressing prospect we may set certain considerations which carry some weight. The whole of this new system of imparting information, to call it by no ruder name, is still in its infancy. It is quite possible of course that it may grow much more powerful and exert a more stifling influence than at present. We must at least be awake to this possibility and beware of it. On the other hand we may safely assume that the whole machinery of broadcasting and television will grow to such an extent that before very long anyone in one part of the world will be able to see or hear a programme from any other part. No doubt powerful efforts will be made to stop this, but it is unlikely that they will be any more successful than efforts have been in our own time to stop listening to forbidden programmes from London or Berlin or Athens. As the programmes multiply, the innate curiosity or perversity of men will lead them to pay attention to much which is not supposed to concern them. In their early days these vast new means of propaganda have indeed been formidable instruments for imposing at least a superficial uniformity, but we may well doubt whether they will keep their supremacy in this direction.

Another source of hope, if not quite of confidence, may be found in the undeniable tendency of men who have a special difficult job to think for themselves. However bad their original education may have been, once they master a technique or a technology, they are almost forced to shape their own philosophy on it. They know it so well that they cannot help noticing at times that facts are not what they are commonly said to be, that there is more than one way of looking at a problem, that what may work as a passable truth in other professions does not work in theirs. This consideration is of first importance in a world where technology of every kind is becoming more complex and more difficult every day. Just because many tasks are more specialized, they demand a higher degree of trained intelligence, and do much of their own training for it. The job makes the man and shapes his critical sense of reality. It is a false criticism to say that specialization narrows the intelligence. On the contrary it is usually when we are specialists in one thing, that we are able to look at other things outside our own sphere with a new detachment and insight. Of course this implies a reputable degree of education, but that too is indispensable if we are to have the specialized technologists whom we need. You cannot set a man to work a difficult machine if he is unable to think within reasonable limits. So in the end it looks as if engineering, which has undoubtedly played into the hands of some of our new bosses by its skill in shaping thoughts, will change its direction and make it easier for those thoughts to be free.

A final objection raised to engineering in social life is that it imposes a standard of culture which lacks the variety and the beauty of the old craftsmanship, that it substitutes the dead products of machines for the fine work of men's hands, that it destroys the grace of life even in the small, select circles where it is still cultivated. Now it is perfectly true that most machine-made articles have not the charm and the distinction of Chippendale or Wedgwood, that concrete lacks the variety of texture and colour to be found in stone, that mass-production must inevitably destroy the old delight of the eyes in things made by hands. It may well be the case that increased production will spoil some of the old fine art of workmanship. But

e should not allow this to get out of proportion nor should we allow wrong conclu-ons to be drawn from it.

There is indeed something to be put on the other side. The more remarkable velopments in architecture in our time are triumphant feats of engineering, and would not be wrong to say that the no less remarkable failures, which we can see undantly around us, are due to a refusal to think logically about what engineering n do for building. The enormous development of scale which it makes possible lls for a new style of architecture, and it is useless to disguise this under old clothing, hether Gothic or Banker's Georgian, or Rothschild Second Empire. The whole rength of a good modern building is that it can, because of its materials, rely on rity of line and simplicity of design. It can really give an effect of height without ch variations as older builders needed to keep it erect. How important this is can seen from the development of American sky-scrapers. The first of them, like the mous "flat-iron building", still kept some traces of Victorian decoration, but they d not need it, and it did nothing for them. Rather it detracted from their essential nplicity of line and balance. The latest buildings, like the Rockefeller Centre or e United Nations Building, have abandoned these and concentrated on the sense height and strength which modern methods make possible. There is no question at the gain is enormous. Not all kinds of buildings should perhaps be built in this y, but it is a remarkable contribution to the aspect of our cities, and it is a triumph engineering controlled by a sense of design and harmony.

If such things can be done for architecture, there is no ultimate reason why they ould not, as our lives become more mechanized, be done for other things. Steam gines have for nearly a hundred years fascinated the imagination of boyhood, and en now they have not entirely lost their place to aeroplanes. But, whether we vel by train or car or aircraft, there is no reason why the machine should not be a light to the eye. It needs some adjustment of vision to realize that this is possible, d it is not enough to think that because an engine or a car goes fast it is therefore autiful. But it is surely a reasonable hope that a new kind of craftsmanship, no s careful, will succeed the old and will provide its own kind of pleasure.

Some historians maintain that civilization becomes degraded as soon as the culti-ted tastes of a few are shared by many. It has even been claimed that this was e of the main factors in the decline of the Roman Empire. This certainly is not ue. In the Roman Empire one of the chief causes of decline was the ever-increasing p between the rich and the poor, and the consequential limitation of arts and ences to a very small class. Nor is the theory true of modern times. The countries ich have shown the greatest intellectual and social advances, France, Great itain, and the United States, have all managed to extend their refinements to an er-increasing class. Of course such a process will show its growing pains. Of urse there will inevitably be failures of taste. Of course there will be mal-justments and mistakes and pretentious impostures. But there is no real reason y a world which relies on machines more than on handicrafts should not in the l produce objects as satisfying as those of the old craftsmen. They will be in re generous supply. They will not be unique treasures. But they will give ight to a far greater number of people than the old system of privileged elegance uld ever do, and in the end man's natural desire to do things well will triumph, l a new kind of grace and charm will emerge.

As the Greeks said "even the gods do not fight against necessity", and for us gineering has become a necessity. It is madness to fight against it, to wish that ad never been. It has brought untold benefits to the world, and if it has often

enough been held responsible for our catastrophes, it is we, and not it, who are to blame. I even cherish the hope that it may help to solve some of our political troubles. In so far as it offers by far the surest and safest way to improve the human lot, is it perhaps not too much to hope that in the end the majority of mankind will see that it is far saner to alter social conditions by its controlled and rapid methods than to revert to violence, which always means that an unforeseen situation is created and that too much has to be done all over again? Man's unique position in the scheme of things lies in his ability to turn nature to his own ends, and if he really knows what these ends are, he should be able to do on an ever-extended scale what he has already begun to do with such imagination and devotion and skill.

CORRESPONDENCE

on a Paper published in Proceedings, Part I, January 1956

Paper No. 6092

The use of blast-furnace slag as a concrete aggregate †

by

Eric Francis Farrington, B.Sc.(Eng.), A.M.I.C.E.

Correspondence

Mr J. H. Thornton (Resident Engineer, Upper Moriston Works) said that some me ago he had visited a breakwater built on the north-east coast by a steelworks in bout 1875. Apparently, no records could be traced to show what materials had been sed in its construction, but it was obvious that blast-furnace slag was the aggregate ad it was understood that cement had not been used as a matrix. Whatever had been sed it was good material, for besides the structure being in good condition a pump-room ad recently been excavated in it at the seaward end and a wall about 4 ft thick and 12 long withstood, without leakage, a head of water of about 20 ft.

It would seem that the Appleby-Frodingham Steel Company could dispose of 20,000 ns of slag per week, but Mr Thornton would like to know if they had considered the use their slag as a partial replacement to cement in concrete by granulating the slag, et-grinding it, and drying it. Dry powdered slag would be a higher priced product than ushed slag.

The matrix of concrete made with wet-ground granulated slag had a bluish colour when oken into, and it would be interesting to learn whether both matrix and aggregate of ncrete with crushed slag was bluish or just the aggregate alone. If the matrix was also ue, that might suggest some action between cement and slag.

The Author, in reply, stated that finely ground granulated slag had not been used at ppleby-Frodingham in partial replacement of cement because circumstances had never et favoured its use. However, Appleby-Frodingham granulate was now being used in e manufacture of Trief cement for a current construction in the south-west of England. her granulated slags had been used for similar purposes both in Britain and abroad. iere seemed no doubt that it could be so used wherever the setting characteristics were lvantageous or otherwise acceptable.

He was not sure what Mr Thornton had in mind when referring to the relative costs of finely ground granulate and a crushed (air cooled?) slag. The relevant comparison was rely with the cement which it replaced rather than with the coarse aggregate. He had, wever, been concerned to avoid all reference to relative costs in his original contribuon for fear of tainting what was intended only as a modest record of fact with any ggestion of commercial interest. But the fact was, as was generally well known, that economic case could be made for using blast-furnace slags which complied with the levant British Standards.

† Proc. Instn Civ. Engrs, Part I, vol. 5, p. 56 (Jan. 1956).

On the question of colour, the Author himself would be interested to learn the reason. He had been told that it was attributable to minute quantities of iron salts, but since it was clearly not deleterious to the concrete or to embedded mild steel at Appleby-Frodingham, he had not considered the cause, or its effect, very important. His impression was that the colour was mainly confined to the matrix. Its occurrence was not universal in all slag concretes; but where it did occur, it was always more noticeable towards the centre of a mass, and seldom approached closer than a few inches to an exposed face. Certainly some chemical interaction between the constituents was involved, possibly facilitated by the heat of hydration or the surplus water remaining in the heart of the concrete after hydration was complete. If that was so, and the colour was at all suspect under certain conditions, it was another argument for careful control of water/cement ratios.

The Author expressed his thanks to the Institution for taking notice of so modest a contribution and to those who had written to him personally. He was of the opinion that the use of slag was a subject which could be better understood, particularly since its use and applications must become of increasing importance as sources of traditional natural materials diminished.

CORRESPONDENCE

on a Paper published in Proceedings, Part I, July 1956

Paper No. 6094

"The design and construction of Aden oil harbour" †

by

John Elliott George Palmer, M.A., M.I.C.E., and
Harold Scrutton, M.I.C.E.

Correspondence

Mr A. B. Hicks (Engineer, Maritime Branch, Department of Works, Australia) bserved that careful planning had eliminated overhead welding, a praiseworthy objective ot always fully appreciated. Much of that welding was in the diagonal bracing of the tty heads—bracing required to bring the rakers of many bents into play to resist horiontal forces. However, reinforced concrete beams nearly 40 ft deep spanned the top of he headstocks. Were not those beams alone sufficient to bring the rakers into action? ossibly, the precast soffit slabs led to some doubt whether the slab would act as described, ut a slight thickening of the in-situ slab, with rods welded to the headstock flanges and ent up into the in-situ slab, should overcome that difficulty.

Since the kinetic energy absorbed by a rubber buffer was proportional to its volume, hereas the impact force was proportional to the area normal to it, was there any objection an alternative buffer 25 in. dia. by 50 in. long, thus giving the same kinetic-energy bsorption but decreasing the force on the jetty by 38%. It would entail a deflexion of 5 in. but that would be acceptable at an oil berth. Tests carried out at the Central esting Laboratory of the Commonwealth Department of Works showed that, for a ngth/diameter ratio of 6, a rubber cylinder would be unstable, but by making the buffer five laminations separated by thin steel spacers (with clearance fit on a central rod) the uffer acted almost as if the ratio were unity. Indications were that the suggested buffer ould be quite stable in one piece; with a ratio higher than 2 the central rod was a comication, and consideration had also to be given to the effect of the change of elevation of e fender pile head due to its rotation.

Mr Hicks asked if there was available any information supplementary to that given in able 1, particularly in the cases where the energy taken by the fender exceeded 50% of e ship's energy. Blows were classified only as "bow" or "stern"; were there any in ality "amidships"?

The Authors, in reply, agreed that the reinforced concrete deck to the jetty could ve served as a beam and the diagonal steel bracing could then have been omitted. areful consideration had been given to alternative designs on those lines—in the extreme se omitting the whole of the welded steelwork and using the reinforced concrete deck

† Proc. Instn Civ. Engrs, Part I, vol. 5, p. 348 (July 1956).

slab in its place. Substantial diagonal bracing would, however, have been necessary while the raking piles were being driven, as well as while the jetty deck was being concreted, since the whole structure had been very flexible until connected to the raking piles. The alternative designs, therefore, would have required considerably more temporary steel-work.

With regard to the proportions of the rubber blocks used for the fenders, as Mr Hicks had stated, the stability of the block was dependent on the length/diameter ratio, and the block selected had been such that its stability was not in question, even if over the years there might be some slight exterior deterioration of the rubber. Another consideration in fixing the travel of the fenders had been the flexibility of the fender pile selected. In Table 1 the first impact of a ship had been classified as "bow" or "stern" in order to divide those blows into broad categories, with a view to observing any tendencies one way or the other. Since, however, the fender groups parallel to the jetty face were 165 ft apart, centre to centre, and some of the ships berthing were more than 700 ft long, when considered from the point of view of the proportion of the energy being imparted to the jetty, they might well, as Mr Hicks had inferred, be considered as blows more nearly amidships

ELECTION OF ASSOCIATE MEMBERS AND ASSOCIATE

The Council at their meetings on 19 June and 17 July, 1956, in accordance with By-law 14, declared that the following had been duly elected:

Associate Members

ADAMSON, WILLIAM SCOTLAND, B.Sc. (*St Andrews*), Grad.I.C.E.
ALLEN, FRANCIS FREDERICK, B.Sc. (*Birmingham*).
ALLEN, NORMAN ROBERT, Grad.I.C.E.
ANGWIN, JOHN OSBORNE, B.Sc.(Eng.) (*London*), Grad.I.C.E.
ANDREWS, JOHN MELVILLE, B.Sc. (*Cape Town*).
ANNAN, JOHN DOUGLAS.
ARNOLD, RAYMOND HARRY.
ASTBURY, RAYMOND.
ATTWOOD, BASIL BRUCE, B.Sc. (*Witwatersrand*).
AYRES, DEREK.
BACON, ROGER, B.Sc.(Eng.) (*London*), Grad.I.C.E.
BADENOCH, GEORGE STUART GILCHRIST, Grad.I.C.E.
BAILEY, DEREK BRUCE, B.Sc.(Eng.) (*London*), Grad.I.C.E.
BANKS, WILLIAM GEORGE, B.C.E. (*Melbourne*).
BARBER, DAVID GARSTON, B.Sc.(Eng.) (*London*), Grad.I.C.E.
BARKER, JOHN ERNEST, Stud.I.C.E.
BARRY, MICHAEL AUGUSTINE, B.E. (*National*), Grad.I.C.E.
BARSBY, JOHN ROSSOLL, B.Sc. (*Belfast*), Grad.I.C.E.
BARTLETT, JOHN VERNON, B.A. (*Cantab.*), Grad I.C.E.
BASSON, PAUL STEPHAN DONALD, B.Sc. (*Cape Town*).
BEALE, RICHARD ARTHUR ST JOHN, M.A. (*Cantab.*).
BEKHOR, MAURICE EZRA, B.Sc. (Eng.) (*London*).
BELLMAN, ARTHUR FRANCIS.
BETTESS, FRED, B.Eng. (*Liverpool*).
BICKLEY, GORDON THOMAS, B.Sc. (*Witwatersrand*).
BORROWMAN, PHILIP RONALD, B.Sc. (*Edinburgh*).
BEAK, WILLIAM ROBERT JENNER, B.Sc. (Eng.) (*London*), Grad.I.C.E.
BEARD, ALAN HOWARD COUSENS, Grad. I.C.E.
BEATTIE, JOHN, Grad.I.C.E.
BERRY, DEREK WILFRED, Grad.I.C.E.
BOSHER, CHARLES WILLIAM.
BOUGHEY, JOHN ERIC, B.Sc. (*Birmingham*).
BRADLEY, DONALD RAYMOND, B.Sc.(Eng.) (*London*), Grad.I.C.E.
BRAZIER, BRIAN CHARLES, B.A. (*Cantab.*), Grad.I.C.E.
BRENTNALL, PETER HENRY, Grad.I.C.E.
BROADBENT, EARLE GEORGE, B.Sc. (*Glasgow*), Grad.I.C.E.
BROCKLEHURST, FRANK.
BROMELL, ROY YEARSLEY.
BROOKS, REGINALD WALTER.
BROWN (*Mrs*), DOROTHY MARY MAUD, B.Sc. (*Bristol*).
BROWN, IAN DURNO.
BRUNT, HUGH MICHAEL, B.Sc. (*Wales*), Grad.I.C.E.
BUCKTHORP, LAWRENCE WILLIAM.
BURMEISTER, IVAN AUGUST, B.Sc. (*Cape Town*).
BURTON, JOHN, B.Sc.(Eng.) (*London*).
CAINE, RAYMOND ALFRED, Grad.I.C.E.
CALDERWOOD, WILLIAM, B.Sc. (*Glasgow*).
CALDWELL, JOHN ALAN, Grad.I.C.E.
CAMPBELL, JAMES MORELAND.
CAMPKIN, WILLIAM DENIS, B.Sc. (Eng.) (*London*), Grad.I.C.E.
CANDISH, ALLAN ALFRED.
CARLSSON, BERNARD LINDHOLM, B.Sc. (*Witwatersrand*).
CARSON, JAMES HUMPHREYS, B.Sc. (*Belfast*), Grad.I.C.E.
CASWELL, ARTHUR HUGH, B.Sc.(Eng.) (*London*), Grad.I.C.E.
CHAMBERLAIN, GORDON RODNEY, B.Sc. (Eng.) (*London*).
CHAPMAN, DAVID JOHN, B.Sc.(Eng. (*London*), Grad.I.C.E.
CLARK, PETER GEOFFREY, B.A. (*Cantab.*), Grad.I.C.E.
CLARKE, GEOFFREY HERBERT, B.E. (*Queensland*).
COARD, CHARLES WALTON RICHARD RUMNEY, Grad.I.C.E.
COELHO, JOHN WILSON, B.Sc.(Eng.) (*London*).
CONWAY, PETER REGINALD, B.Sc. (*St Andrews*).
COWIE, COLIN ALFRED, B.E. (*New Zealand*).
CRAIGIE, ALLAN SINCLAIR, Grad.I.C.E.
CRAMER, LEON, B.Sc. (*Leeds*).
CREANEY, TERENCE ALEXANDER, B.Sc. (Eng.) (*London*), Grad.I.C.E.
CROCOMBE, COLIN ALSTAN, B.E. (*New Zealand*), Grad.I.C.E.
CULVERWELL, DAVID RODNEY, B.A. (*Oxon*), Grad.I.C.E.

CUPITT, PETER, B.Sc. (*Birmingham*), Grad. I.C.E.
CUTHBERT, KEITH HENRY ROBSON, B.Sc. (*Leeds*), Stud.I.C.E.
DAVIES, BENJAMIN ROYCE, B.Sc. (*Wales*).
DAVIES, ROSS PARRY, B.Sc. (*Cape Town*).
DAWSON, LEONARD CECIL.
DEACON, RONALD COLIN, B.Sc.(Eng.) (*London*), Grad.I.C.E.
DEVEREUX, WALTER FRANK, B.Sc. (Eng.) (*London*), Grad.I.C.E.
DICKENS, WILLIAM JAMES, B.Sc.(Eng.) (*London*), Grad.I.C.E.
DODDS, GEORGE SMITH, Grad.I.C.E.
DODGSON, KENNETH, B.Sc. (*Edinburgh*).
DOWNEY, VICTOR MICHAEL, Grad.I.C.E.
DOWNING, ROY BERTRAM.
DRAPER, JAMES GORDON, B.Sc. (*Witwatersrand*).
DUDLEY, GEORGE STEWART BENFIELD GUILDFORD, B.Sc. (*Witwatersrand*).
DUNCAN, JOHN, B.Sc. (*Glasgow*).
ECCLESTON, WILLIAM MONTAGUE DELAIR, B.Sc.(Eng.) (*London*).
EDGAR, THOMAS LAWSON, B.Sc. (*Glasgow*).
EDKINS, ANGUS, Grad.I.C.E.
EDWARDS, PAUL HARPER DICKINSON, Grad.I.C.E.
ELLEN, PETER EDINGTON, B.E. (*New Zealand*).
EMERSON, FRANK KAY.
FARROW, HILARY FRANCIS, B.Sc.(Eng.) (*London*), Grad.I.C.E.
FERNANDO, MERENNEGE RATNAPHALA, B.Sc.(Eng.) (*London*), Grad.I.C.E.
FINNEGAN, HENRY JOSEPH, B.E. (*National*).
FISHER, DOUGLAS MACKAY.
FLAXMAN, EDWARD WASLEY, B.Sc.(Eng.) (*London*), Grad.I.C.E.
FLINT, ANTHONY RAY, B.Sc.(Eng.) (*London*).
FLINT, PETER INGLEBY, *Sqdn. Ldr.*
FORT, GEOFFREY BUCHANAN, B.Sc. (*Manchester*), Grad.I.C.E.
FRIEND, HENRY WILLIAM, Grad.I.C.E.
GARA, CZESLAW ANTONI JERZY.
GARDINER, DOUGLAS WYPER, B.Sc. (*Glasgow*), Grad.I.C.E.
GEACH, TREVOR TRENLEY WARD, Grad. I.C.E.
GEORGE, ALVIN BRIAN, B.Sc. (*Birmingham*), Grad.I.C.E.
GIBBS, LEONARD THOMAS, Grad.I.C.E.
GILBERTSON, ALEXANDER KENNETH GEORGE, B.Sc.(Eng.) (*London*).
GILL, HENRY WARD, B.Sc.(Eng.) (*London*).
GILLIES, GEORGE ALBERT HENRY, Grad. I.C.E.
GIN, KENNETH YING DOON, B.C.E. (*Melbourne*).
GODDARD, PHILIP DENNIS.
GOLLAN, GRAHAM ARTHUR, B.Sc.(Eng.) (*London*), Grad.I.C.E.
GOODMAN, ROBERT HENRY.
GOODWIN, RONALD RICHARDS, B.Sc. (*Nottingham*), Grad.I.C.E.
GORDON, ALEXANDER HAY, B.Sc. (*St Andrews*).
GOUGE, RICHARD LING, B.A. (*Cantab.*), Grad.I.C.E.
GOUGH, JOHN NOEL, B.Sc. (*Birmingham*), Grad.I.C.E.
GOULD, PETER, B.Sc.(Eng.) (*London*), Grad.I.C.E.
GRANFIELD, ERIC FRANCIS.
GRANGER, RAYMOND NEWELL, B.Sc.(Eng.) (*London*), Grad.I.C.E.
GRAY, ANDREW MUNRO, B.Sc. (*Glasgow*), Grad.I.C.E.
GRAY, ROBERT EDMUND ALEXANDER, B.A., B.A.I. (*Dublin*).
GRICE, JOHN ROBERT, B.Sc.Tech. (*Manchester*), Grad.I.C.E.
GRIFFITHS, CECIL THOMAS, B.Sc.(Eng.) (*London*).
HALE, PETER WILLIAM, B.Sc.(Eng.) (*London*), Grad.I.C.E.
HART, NOEL HENRY ALFRED, B.Sc. (*St Andrews*).
HAWKINS, ALEXANDER THOMAS, B.Sc. (Eng.) (*London*), Grad.I.C.E.
HEATH, LESLIE WILLIAM ALBERT, Grad. I.C.E.
HENDERSON, FRANCIS MARTIN, B.E. (*New Zealand*).
HENDERSON, FRANK ALEXANDER, B.Sc. (Eng.) (*London*).
HENDLY, THOMAS ELLIOTT, B.A., B.A.I. (*Dublin*).
HILLMAN, DENNIS JOSEPH.
HIRD, HAROLD VERNON, B.A. (*Cantab.*), Grad.I.C.E.
HIRST, ROY OLIVER, Grad.I.C.E.
HOLLAND, JACK DOLMAN, B.Sc. (*Birmingham*).
HOLLINGWORTH, DAVID JOSEPH PASCOE, B.Sc. (*Birmingham*), Grad.I.C.E.
HOLMES, FRANCIS JOHN, B.A., B.A.I. (*Dublin*).
HOLT, CHARLES WILLIAM, B.Sc.(Eng.) (*London*).
HOLT, CLIFFORD FREDERICK, Grad.I.C.E.
HOOPER, IAN ROSS, B.A. (*Cantab.*), Grad. I.C.E.
HORABIN, JOHN BERNARD, B.Sc.(Eng.) (*London*).
HOWLETT, JOHN HENRY DEWSE, Grad. I.C.E.
HOYLE, NORMAN, B.Sc.Tech. (*Manchester*), Grad.I.C.E.
HUTT, EDWARD ALEXANDER, B.Sc. (*New Zealand*).

-lis, Douglas Johnstone, B.Sc. (*Aberdeen*), Stud.I.C.E.
-ram, Thomas George Lovatt, B.Sc. (Eng.) (*London*).
-ing, John Antony, Grad.I.C.E.
-ckson, Brian James, B.E. (*New Zealand*), Grad.I.C.E.
-ckson, John George, B.Sc.(Eng.) (*London*).
-mes, Dennis Frederick, Grad.I.C.E.
-frey, Michael Henry, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-hn, Maldwyn Griffith, B.Sc. (*Wales*).
-hnson, Alan Stanley, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-hnson, Kenneth Charles, Grad.I.C.E.
-hnston, John Campbell, M.A., M.A.I. (*Dublin*), Grad.I.C.E.
-nes, William Tudor Foulkes.
-oe, Dennis Victor, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-lway, Kenneth Clement Stuart, B.A. (*Cantab.*).
-mp, John Richard.
-ysser, Andreas Jacobus, B.Sc. (*Cape Town*).
-ncaid, William, B.Sc. (*Glasgow*), Grad. I.C.E.
-ng, David Leonard, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-ng, John David, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-rby, Thomas Henry, Grad.I.C.E.
-rkaldy, Ian Drummond, Grad.I.C.E.
-rd, Bowman Stiven, B.Sc. (*Aberdeen*).
-nsdall, Gerald, B.Sc.(Eng.) (*London*).
-pham, Nigel Frederick, B.A. (*Cantab.*).
-yfield, Peter, Grad.I.C.E.
- Clerc, Brian Richardson, Grad. I.C.E.
-gg, Leslie Alexander, B.Sc.(Eng.) (*London*).
-wis, Kenneth David.
-esey, Stanley Robert George, B.Sc. (Eng.) (*London*).
-aring, Maurice Wesley, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-raine, Robert Kinlayside, B.Sc. (*Glasgow*), Grad.I.C.E.
-wes, Arthur, Stud.I.C.E.
-etchford, Michael Alfred Cecil, B.Sc.(Eng.) (*London*), Grad.I.C.E.
-Carthy, Denis Walter Charles, M.B.E., M.A. (*Cantab.*), *Lt-Col.*
-Cash, James Alexander, B.Sc. (*Glasgow*).
-cDowell, James Roughan Kenneth, B.A. (*Cantab.*), Grad.I.C.E.
-Kie, Thompson Joseph, B.E. (*New Zealand*).
-ckley, Frank Rainsford.
-cky, Robert Graham, B.E. (*New Zealand*), Grad.I.C.E.

Mahalingam, Sivapragasam, Grad.I.C.E.
Maheswaran, Arumugan, B.Sc.(Eng.) (*London*).
Mann, Frank Thomas, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Mardel-Ferreira, Joseph Charles, B.Sc. (Eng.) (*London*).
Mead, Ronald James, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Minch, David Berchmans, B.A., B.A.I. (*Dublin*), Grad.I.C.E.
Mitchell, David, Grad.I.C.E.
Mitchell, John Edward, M.A. (*Cantab.*), Grad.I.C.E.
Mohamed, Ali Sheikh.
Morgan, Richard Palmer.
Morgan, William Bain, B.Sc. (*Belfast*), Grad.I.C.E.
Motyer, Arthur Edmund, B.Sc. (*Cape Town*).
Munn, Harvey, B.Sc. (*Glasgow*), Grad. I.C.E.
Murphy, Eugene Anthony, B.Sc. (*Belfast*), Grad.I.C.E.
Newing, John Lewis, B.Sc. (*Bristol*), Grad.I.C.E.
Nicholas, Rhys John.
Nicholl, Thomas Parker, B.A. (*Cantab.*), Grad.I.C.E.
Nichols, John Russell, B.Sc. (*Cape Town*).
Nield, Hugh Sankey Thomas, B.Sc. (Eng.) (*London*).
Noble, Ronald Edward, B.Sc.(Eng.) (*London*).
Norman, Alan Geoffrey, B.Sc. (*Nottingham*), Grad.I.C.E.
Norman, Dudley Graham, M.Sc. (*South Africa*).
Norman, Jack, B.Sc. (*Cape Town*).
Onuorah, Albert Ben, B.Sc. (*Glasgow*).
Otto, Norman Douglas.
Parker, Alan Scott, M.Sc. (*Leeds*), Grad. I.C.E.
Paterson, Colin Alexander, B.A. (*Cantab.*), Grad.I.C.E.
Pathmanathan, Sabharatnam, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Payton, Alan William, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Perkins, Arthur.
Phillips, George Lance, B.Sc.(Eng.) (*London*).
Pitt, Charles Henry Enoch.
Postlethwaite, Roger Kelsall, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Powell, Philip John.
Priestley, Clive Nigel, B.A. (*Cantab.*).
Raikes, Roger Melville Taunton, B.A. (*Oxon*), Grad.I.C.E.
Raine, James Brailsford, B.A. (*Cantab.*), Grad.I.C.E.
Read, John, B.A. (*Oxon*), Stud.I.C.E.

Richards, Gwillim Thomas, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Riding, Christopher Rolleston, B.A. (*Cantab.*), Grad.I.C.E.
Riley, Richard Woodburne, M.A. (*Cantab.*), Grad.I.C.E.
Robertson, Raymond Lewis, B.Sc. (*Witwatersrand*).
Russell, Hamish Fleming, B.Sc. (*Glasgow*), Grad.I.C.E.
Saunders, Geoffrey Charles, B.Sc. (Eng.) (*London*), Grad.I.C.E.
Saunders, Reginald Edward Knox, B.Sc. (*Witwatersrand*).
Savage, Philip Fison, M.Sc. (*Witwatersrand*).
Schaffner, Robert Hastings, B.Sc. (*Witwatersrand*).
Schwartz, Pierre Gerard.
Scott, William Pirie, B.Sc. (*Glasgow*), Grad.I.C.E.
Semple, John Ferguson, B.Sc. (*Aberdeen*).
Shepherdson, Lewis.
Singh, Sandhu Pritam, B.Sc. (*Glasgow*), Grad.I.C.E.
Sinkinson, Geoffrey, B.Sc.(Eng.) (*London*).
Skepper, Herbert Gordon, B.Sc.Tech. (*Manchester*).
Skowronski, Mieczyslaw.
Sparks, Geoffrey Vincent, B.C.E. (*Melbourne*), Grad.I.C.E.
Springfield, John, B.Sc. (*Nottingham*), Grad.I.C.E.
Stacey, Leslie Edward Selby.
Staples, Kenneth Derek, Grad.I.C.E.
Stephenson, Herbert Douglas, B.Sc. (*Durham*), Grad.I.C.E.
Steward, Peter Russell.
Stewart, Donald, B.Sc.Tech. (*Manchester*), Grad.I.C.E.
Stewart, James Campbell, B.Sc. (*Glasgow*).
Sullivan, David William, B.E. (*New Zealand*).
Summers, Leslie, B.Sc.(Eng.) (*London*).
Summersgill, Keith, B.Sc. (*Leeds*).
Swales, Peter Brian, B.A. (*Cantab.*), Grad.I.C.E.
Tanner, Roy Galbraith, B.Eng. (*Liverpool*), Grad.I.C.E.
Tapping, David William, B.Sc.(Eng.) (*London*), Grad.I.C.E.
Tchernavin, Andre.
Tebbutt, Ronald Norman, B.Sc. (*Birmingham*), Grad.I.C.E.
Teraszkiewicz, Miroslav Jerzy.
Thomas, David Howard, B.A. (*Oxon*), Grad.I.C.E.
Thomson, Walter John.
Thriscutt, Herbert Sydney, B.Sc.(Eng. (*London*).
Tidy, Anthony Brian Stafford, B.Sc. (*Birmingham*), Grad.I.C.E.
Townsend, Michael Ingham, B.Sc. (*Manchester*), Grad.I.C.E.
Townshend, Richard Chambrey, B.A (*Cantab.*), Grad.I.C.E.
Trowbridge, Michael Burton, B.Sc (Eng.) (*London*), Grad.I.C.E.
van Gelder, Albert.
Vrettos, Christos, B.Sc. (*Witwatersrand*)
Walker, Adam Fulton, Grad.I.C.E.
Wallace-Jones, George Maurice, B.A (*Cantab.*), Grad.I.C.E.
Walsh, John, B.Sc. (*Nottingham*), Grad I.C.E.
Ward, John, B.Sc. (*Nottingham*), Grad I.C.E.
Waters, Arthur Jack, B.Sc.(Eng. (*London*).
Watt, James Chalmers Grant, B.E (*New Zealand*), Grad.I.C.E.
Watts, David Ian, B.A., B.A.I. (*Dublin*)
Wellings, Leslie Bernard, B.Sc.(Eng. (*London*), Grad.I.C.E.
Wherrett, John, B.Sc. (*Bristol*).
Whicker, Ronald Frederick, B.Sc (Eng.) (*London*).
Whitlock, Christopher John, B.Sc (Eng.) (*London*).
Whitehead, Fernley Sidney, B.Sc (*Witwatersrand*).
Williams, Peter Norman, Grad.I.C.E.
Wilson, Brian Harold, B.A. (*Cantab.*) Grad.I.C.E.
Wilson, George Thomas Eunson, B.Sc (*Edinburgh*), Grad.I.C.E.
Winder, Alexander John Henry, B.A (*Oxon*).
Winstanley, William Kenneth, B.Sc (*Manchester*).
Witthaus, Kenneth Gabriel, B.Sc (*Witwatersrand*).
Wolley, Charles William, Grad.I.C.E.
Wood, Arthur Stanley, B.Sc. (*Belfast*) Grad.I.C.E.
Woolf, Brian Joseph, B.Sc. (*Birmingham*).
Wootton, Norman Allan, B.Sc. (*Wales*)
Wordsworth, John, B.Sc. (*Witwatersrand*).
Wormald, Peter Shaw, M.Sc. (*Leeds*) Grad.I.C.E.
Wyatt, William Ronald Macdonald B.Sc. (*Glasgow*), Grad.I.C.E.
Yogarajah, Chellappah, B.E. (*Queensland*).
Young, William Alexander, B.Sc (*Glasgow*), Grad.I.C.E.

Associate

Allen, Professor Deryck Norman de Garrs, M.A. (*Oxon*).

DEATHS

't is with deep regret that intimation of the deaths of the following has been eived.

Members

BERT BRUCE, B.Sc. (E. 1933, T. 1943).
OMAS INGHAM DIXON, M.A., M.A.I. (E. 1913).
CAR FABER, C.B.E., D.Sc. (E. 1911, T. 1924).
RDON THOMSON FREW (E. 1925).
EXANDER ROSS FYFE (E. 1918, T. 1936).
NEST JOHN HAMLIN, D.Sc., F.R.S. (E. 1919, T. 1925) (former Member of Council).
RTRAM CHARLES HAMMOND, C.B.E. (E. 1915, T. 1932).
DDLE HEDLEY (E. 1907, T. 1928).
ORGE NICHOLAS LOGGIN, C.M.G. (E. 1908, T. 1922).
LLIAM ARTHUR MOYERS, B.A., B.A.I. (former Member of Council).
GH JOHN HARRY STEDMAN, O.B.E. (E. 1916, T. 1926).
ARLES EGREMONT STOTHERD (E. 1896, T. 1922).
LLIAM THOMAS TAYLOR (E. 1918).
HN STEVENSON YOUNG, B.Sc., B.Eng. (E. 1910, T. 1926).

Associate Members

NEST JAMES BARRETT (E. 1891).
LLIAM BOOTH (E. 1918).
LLIAM TRENTHAM SYMONS BUTLIN, M.B.E. (E. 1904).
ENNETH VINCER CUTHBE (E. 1911).
ORGE STEPHEN ANTHONY GUNDRY, B.Sc. (E. 1930).
EPHEN JAMES HUNTER (E. 1910).
URTENAY ADRIAN ILBERT, B.A. (E. 1916).
AVID LAWSON (E. 1937).
OBERT ALEXANDER STURGEON (E. 1912).
LLIAM THOMAS (E. 1902).
IOMAS AUBREY WATSON (E. 1901).

Graduate

CHAEL ALLEN WILCOX (A. 1952).

OBITUARY

ROBERT BLACKBURN, O.B.E., who was born on 28 March, 1885, died on 10 September, 1955.

He was educated at Leeds Boys Modern School, at Leeds University, and in Germany.

He was apprenticed to Thomas Green & Sons of Leeds, and also worked in several large engineering firms in Germany. He received his aeronautical training in Paris where he designed his first aeroplane in 1909. He attempted his first flight from Saltburn sands in the same year, but with little success. An improved machine built towards the end of 1909, proved completely successful and he then began the construction of further models. Notable among his early designs was an all-steel military monoplane produced in 1911.

To stimulate interest in aviation during the years 1910 to 1914 he established flying schools at Filey and Hendon. The founding of the Blackburn Aeroplane and Motor Company at Leeds followed in June 1914. During the First World War his company supplied large numbers of military aircraft and were responsible for the design and construction of the first successful torpedo-carrying aeroplane.

In 1924 he established a flying school at Brough and in the same year initiated a survey of the main African air route from Khartoum to Kisumu.

In 1925 he secured a contract for the organization of the Greek Naval Aircraft factory, near Athens. For his services he was decorated by the Greek government.

In 1936 he formed a public company, Blackburn Aircraft Ltd with factories at Brough, Leeds, and Dumbarton, and flying schools at Brough and Hanworth.

He was elected an Associate Member in 1913. He was also a Member of the Institution of Mechanical Engineers, and an Honorary Fellow of the Royal Aeronautical Society.

He is survived by his wife and two daughters.

JOHN EDWARD BOSTOCK, O.B.E., who was born on 26 September, 1878, died on 16 March, 1956.

He was educated at Marlborough College, and at University College, London.

He commenced his professional career with Messrs Coode, Son, and Matthews. In 1901 he was appointed Assistant Engineer, Admiralty Harbour, Dover. From 1909 to 1915 he was Engineer in Charge, Gold Coast and Sierra Leone harbours.

Returning to Europe in 1915 he served with the Royal Engineers in France and was concerned with inland water transport and the construction and maintenance of canals and bridges. He attained the rank of Major and was awarded the O.B.E. (Military Division).

In 1919 he became Resident Engineer for the Lewis and Harris Development Scheme and was responsible for the construction of harbours, roads, bridges, factories, housing and drainage projects.

He returned to Africa in 1921 and was appointed Ports Engineer for the Nigerian Government and was in control of all Nigerian harbours.

From 1935 to 1939 he was Resident Engineer (Technical) to the Egyptian Government for the remodelling of the Assiut Barrage.

From 1940 to 1944 he fulfilled engineering duties at the Estuary Oil Berth, onmouth.

He was elected an Associate Member in 1904, and was transferred to the class of mbers in 1916. For his Paper "Remodelling of the Assiut Barrage, Egypt", he s awarded a Telford Premium.*

He is survived by his wife.

GORDON RATTRAY FENTON, O.B.E., who was born on 18 June, 1895, died 13 January 1956.

He received his general education at Harris Academy, Dundee, and his practical ining under Mr J. H. Hannay Thompson, M.I.C.E., General Manager of the ndee Harbour Trust.

During the First World War he served in the Royal Field Artillery as gunner and let.

In 1920 he returned to the Dundee Harbour Trust and was appointed Assistant gineer, responsible for general dock maintenance, including railway layout.

In 1923 he became Assistant Engineer, Port Development Department, Hong ng, and was concerned with construction of blockwork quay walls, reclamation rks, dredging, and surveys.

In 1926 he joined Messrs Coode, Wilson, Mitchell and Vaughan-Lee, as Assistant gineer, later becoming Chief Assistant and then Resident Engineer for the Kilindini rbour works, Kenya, which included construction of deep-water quays, transit eds, and the ancillary railways, roads, etc.

In 1933 he was appointed Deputy Engineer, and later in the same year Chief gineer to the Aire and Calder Navigation, Leeds, owners of the port of Goole and nals in Yorkshire. Mr Fenton was responsible for general maintenance and con-uction of both canals and docks. He was also Chief Engineer on the Trent Falls provement scheme.

During the Second World War he served as a member of the Goole Port Emergency mmittee under the Ministry of Transport and on the panel of consultants to the ar Office.

In 1943 he was appointed to the Engineer and Railway Staff Corps, Royal Engin-rs, with the rank of Major.

Under the Transport Act of 1947 the Aire and Calder Navigation became a unit the Docks and Inland Waterways Executive, British Transport Commission, and r Fenton was appointed Divisional Engineer, North Eastern Division, a post he ld until his death.

In June 1948 he was awarded the Order of the British Empire.

He was elected an Associate Member in 1925, and was transferred to the class of embers in 1942.

He is survived by his wife, a son, and a daughter.

JAMES PERCY HALLAM, was born on 28 March, 1879. Notification of his cent death was received on 21 March, 1956.

He received his early education at Manchester Central School and from 1893 to 905 studied engineering at Manchester College of Technology.

He entered the service of the Manchester Corporation in 1894 as a junior in the

* J. Instn Civ. Engrs, vol. 14, p. 301 (June 1940).

Hydraulic Power Supply Section and was bound by articles (1896–1900) and unde agreement (1900–1905) to Mr L. Holme-Lewis.

From 1905 to 1910 he served in the Chief Engineer's Drawing Office, engaged o design and operation of steam and electrically driven pumping plant. He assiste in the design, erection, and starting up of the hydro-electric installation in th Longdendale Valley.

He remained on the staff of the Chief Engineer, Manchester Corporation Wate works, until 1926. During that time he was employed mainly on mechanical an electrical work and was responsible for the design and erection of many and varie plants connected with the supply of water to Manchester, including the Thirlme works, the Haweswater Scheme power station, and pumping plants at Chorle Adlington, and Blackrod.

Upon his appointment in 1926 as Chief Mechanical and Electrical Engineer to th Corporation Waterworks he assumed responsibility for the whole of the mechanica and electrical machinery of the Department.

In 1931 he was appointed Chief Engineer, and in 1940 Engineer and Manager o the Manchester Corporation Waterworks, a post which he held until his retiremen in 1945. He was particularly interested in the installation of chlorination plants a various service reservoirs and on the Thirlmere Aqueduct. He also set up a experimental purification plant at Denton and a micro-straining plant at Garnet Bridge, at the junction of the Haweswater and Thirlmere Aqueducts.

He was elected a Member of the Institution in January 1942 and was also a membe of the Institutions of Mechanical, of Electrical, and of Water Engineers.

WILLIAM LOWE LOWE-BROWN, D.Eng., M.Sc., who was born on 13 Febru ary, 1876, died on 20 March, 1956.

He graduated from Victoria University with first-class honours and a universit scholarship for engineering research. He continued his studies at Liverpool Univer sity and later, on the basis of his published works, was awarded his doctorate.

From 1895 to 1897 he was engaged on research and presented to the Institutio a Paper "Elasticity of Portland Cement"[1] for which he was awarded a Jame Forrest Medal and a Miller Prize.

He began his professional career in 1897 under Sir Benjamin Baker and wa concerned with tunnelling and underground railway layout and design for th Central London Railway. From 1898 to 1904 he was Assistant Engineer to th Egyptian Government on constructional work on the first Aswan Dam. For hi later services in connexion with the Assiut Barrage he was honoured with the Orde of Mejediah.

In 1904 he was appointed Resident Engineer with the Pennsylvania Railroad Co New York, and was responsible for the construction of tunnels under the Hudso River. This work he described in a Paper to the American Society of Civil Engineer for which he was awarded the Thomas Fritch Roland Prize.

Moving to South America in 1910 he became Tunnel Engineer, and later Chie Engineer to the Buenos Aires Western Railway Co., and was in charge of the desig and construction of underground railway lines and stations for the city of Bueno Aires. He presented to the Institution a Paper "Buenos Aires Western Railwa Tunnels under the City of Buenos Aires",[2] for which he was awarded a Telfor Premium.

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[1] Min. Proc. Instn Civ. Engrs, vol. 137 (1898–99, Pt III), p. 402.
[2] Min. Proc. Instn Civ. Engrs, vol. 205 (1917–18, Pt I), p. 165.

During part of the First World War he served as a Lieutenant-Colonel in the Royal gineers and was Officer Commanding on construction of the Richborough train ry and wharf. He was transferred to the Royal Marines and was in charge of miralty work at Southwick which involved construction of reinforced concrete vers.

Returning to South America in 1919 he became Assistant General Manager to the enos Aires Western Railway Co., and was also Manager and Technical Adviser to Railway Petroleum Co., Argentina, from the formation of that company in 1921.

In 1925 he became a Consulting Engineer with Sir Murdoch MacDonald and rtners, and was concerned with the Vyrnwy Viaduct, the cast-iron lining for the rsey Tunnel, and shafts and tunnels for power stations at Swansea and Dagenham.

From 1934 to 1938 he was Consulting Engineer to Liverpool Corporation Water mmittee.

He was Author of several technical Papers, including in 1948 "British Practice in m Foundations" for the International Commission on Large Dams.

He was elected an Associate Member in 1902, and was transferred to the class of mbers in 1910. He was also a Member of the American Society of Civil Engineers, Member of the Institution of Water Engineers, and a Member of the Association of nsulting Engineers.

He is survived by his wife.

ROBERT STRIBLEY MURT, O.B.E., who was born on 8 October, 1888, died 2 February, 1956.

He was educated at Penwerris Grammar School, Falmouth, and then became an ticled pupil to the Borough of Falmouth.

In 1908 he joined Cornwall County Council, first as an Assistant, and later as sistant County Surveyor.

During the First World War he served with the Royal Engineers in the Road nstruction Company (Directorate of Roads) in France, and attained the rank of eutenant.

In 1919 he was appointed County Road Surveyor to the Durham County Council, post he held unti 1922 when he became Deputy County Surveyor to Buckingham-ire County Council.

From 1928 until his retirement he was County Surveyor to the Staffordshire unty Council.

In 1945 he was awarded the Order of the British Empire.

He was elected an Associate Member in 1920, and was transferred to the class of embers in 1932.

He is survived by his wife.

GEORGE STOW, O.B.E., who was born on 11 July, 1876, died on 16 January, 56.

He was apprenticed to Messrs Holloway, General Engineers, of Shoreham from 92 until 1896. He obtained his engineering education at Brighton Technical ollege and won a Whitworth Exhibition.

From 1897 to 1901 he was Assistant to Mr Blaber, Consulting Civil Engineer, and otained varied experience of waterworks and sewerage works construction. Mr ow was appointed Chief Engineer to a firm of Public Works Contractors in 1901, a osition which he held until 1910. He saw active service in France from 1915 to

1919 in the Royal Engineers, attained the rank of Captain, and was awarded the O.B.E.

In 1910 he founded the firm of George Stow & Co. Ltd, Waterworks Contractors, of which he was Managing Director up to the time of his death.

Mr Stow was the Author of a Paper[1] presented to the Institution entitled "Portslade and Southwick Drainage, 1902: intercepting sewer and outfall".

He was elected an Associate Member in 1901, and was transferred to the class of Members in 1953. He was also a Member of the Institution of Mechanical Engineers, and a Fellow of the Geological Society.

He is survived by his widow, four sons, and a daughter.

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[1] Min. Proc. Instn Civ. Engrs, vol. 151 (1902–1903, Pt I), p. 327.

CORRIGENDA

Proceedings, Pt I, March 1956.

Paper No. 6114 (Smith and Williamson)—

p. 97, Fig. 9 :—*for* " tip clearance " *read* " diameter clearance."

p. 98, 3rd line from top and 7th line from top :—*for* " tip clearances " *read* " diameter clearances."

Proceedings, Pt I, July 1956.

p. 470, 17th line from bottom :—*for* "1883" *read* "1885."

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